PREDICTING TIME-VARYING ILLUMINANCE IN COMPLEX SPACES WITH LIGHTING CONTROL SYSTEMS

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Predicting Time-Varying Illuminance in Complex Spaces with Lighting Control Systems

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Abstract

In response to environmental concerns, demands for improved energy efficiency and a desire to create a more pleasant working environment; building designers are looking for ways to make better use of natural light. However, whilst natural light is both free and non-polluting, it can also produce high levels of visual contrast and glare, and unwanted heat.

Most current design techniques estimate the natural internal illumination that results from an overcast sky; they do not include the contribution by direct sunlight entering the space, which is often the source of unwanted characteristics. Whilst a sophisticated computer ray-tracing program (RADIANCE) exists that can predict the full range of natural illumination, each prediction can take several minutes (or longer) to calculate. The time required to examine how a natural lighting design behaves over a typical year can therefore be prohibitive. Techniques for estimating the illumination provided by artificial lights also predict illumination under static conditions. Current techniques are therefore unsuitable for examining the dynamic behaviour of a lighting design, which links the automatic control of artificial lights to the changing levels of natural light.

The aim of this research was to develop a computer based lighting design tool that overcomes these limitations. Based on the calculation of lighting coefficients, the numeric relationship between the luminance of light sources and the illuminance they produce, the Dynamic Lighting System (DLS) is able to calculate time-varying illuminance from a combination of natural light and artificial lights controlled by a lighting control system.

The DLS has been written using the platform independent programming language Java. It is therefore able to run unaltered on most computer platforms, although in practice is limited to platforms on which the ray-tracing program RADIANCE will run, as RADIANCE is used to calculate coefficients.

The DLS has been tested by comparing predicted levels of illuminance with levels measured in a test room under real sky conditions. These comparisons showed a high degree of correlation, but with a few large discrepancies. Possible causes of these discrepancies are offered and suggestions made about how they might be eliminated.

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Acknowledgments

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Nomenclature

BRE	Building Research Establishment
BRS	Building Research Station
C	Fractional Cloud Cover
CD	Coefficient of Determination
CD-ROM	Compact Disk – Read Only Memory
CIE	Commission Internationale de l'Éclairage
DLS	Dynamic Lighting System
Eed	Diffuse Horizontal Irradiance (W/m^2)
Eeg	Global Horizontal Irradiance (W/m^2)
Ees	Direct Normal Irradiance (W/m^2)
Ees_0	Normal Extraterrestrial Irradiance (W/m^2)
ERC	Externally Reflected Component
ET	Equation of Time
EU	European Union
Evd	Diffuse Horizontal Illuminance (lux)
Evs	Direct Normal Illuminance (lux)
GHG	Greenhouse Gases
GUI	Graphical User Interface
HTML	Hyper-Text Mark-up Language
IES	Illuminating Engineering Society
IN	Nebulosity Index
IRC	Internally Reflected Component
K_B	Direct Luminous Efficacy (lm/W)
K_D	Diffuse Luminous Efficacy (lm/W)

LAT	Local Apparent Time
LMT	Local Mean Time
lv	Relative luminance of a point on the sky hemisphere
Lv	Luminance of a point on the sky hemisphere (Cd/m^2)
m	Optical Air Mass
MBE	Mean Bias Error
PC	Personal Computer
RE	Relative Error
RMSE	Root Mean Square Error
SBS	Sick Building Syndrome
SC	Sky Component
T_L	Linke Turbidity Factor.
TRY	Test Reference Year
Z	Solar Zenith Angle (radians)
γ	Angle between a point on the sky hemisphere and sun position (radians)
γ_S	Solar Altitude (radians)
δ_R	Raleigh Optical Thickness
ε	Sky Clearness
Δ	Sky Brightness
ζ	Zenith Angle of a point on the sky hemisphere (radians)
θ	Zenith Angle (radians)
ϕ	Azimuth Angle (radians)

Chapter 1

Introduction

1.1 The need for illumination

Human beings need illumination to enable them to perform visual tasks. Inside buildings, this illumination can be provided by natural light, artificial light, or a combination of the two. One of the aims of lighting design is to create an environment that provides sufficient levels of illumination without causing discomfort to the occupants. Occupants of buildings that are wholly (or predominantly) lit by artificial light appear to experience more sight related problems than those in naturally lit buildings. Insufficient exposure to natural light may be linked to the physiological and psychological effects associated with Sick Building Syndrome (SBS) [Raw 92].

1.2 Environmental issues

In response to environmental concerns such as global warming and conservation of fuel sources, architects and designers are looking for ways to reduce overall energy consumption in buildings. If more internal illumination can be provided by natural light, the need for artificial lights and the electrical energy they consume can be reduced. By the application of 'Best Practice' guidelines for the use of energy in offices, it is estimated that the annual electrical energy consumed by lighting in non-domestic buildings can be reduced by around 50%. For a standard air-conditioned building with an area of 5,000 m^2, this equates to an annual saving of approximately £7,450 [DETR 98].

In addition to the consumption of electrical energy, artificial lights can also produce an unwanted heating effect. Increased use of natural light therefore has the potential to also reduce the electrical energy consumed by air conditioning that may be needed to remove excess heat. Natural light, in particular bright sunlight, can however have a significant heating effect.

Careful design of fenestration is therefore required if the potential energy reduction that greater use of natural light offers is to be achieved.

A reduction in the use of electrical energy can potentially reduce emissions of CO_2, one of the major Greenhouse Gases (GHG). The need to stabilize global GHG emissions was outlined in Article 2 of the United Nations Framework Convention on Climatic Change [UN 92]. The Kyoto Protocol [UN 98] committed European Union (EU) countries to reduce overall GHG emissions to a level 8% below the 1990 level. This level must be achieved during the period 2008 to 2012.

1.3 The use of computer simulation in lighting design

When a building is designed, computer simulation programs can be used to calculate levels of internal illumination. These vary in complexity from simple programs with limited accuracy that calculate only daylight, to highly sophisticated and accurate programs that can calculate daylight, sunlight and artificial light. It can however take several minutes (or longer) to calculate the illuminance at a single point when there are complex inter-reflections. This time penalty may not be significant if only a few values are required, but to examine how illumination changes over long periods, e.g. hourly intervals throughout a year, simulation times can be prohibitive.

One way to reduce electrical energy consumption is to automatically control the switching of artificial lights, so that they are only used when a space is occupied and when natural illumination is inadequate. However, a limitation in the ability of currently available computer simulation programs to predict how illumination varies with time makes it difficult to incorporate lighting control systems into the simulation.

The subject of this research is the development of a lighting design tool that addresses these limitations.

1.4 Aims of the research

The aim of the research was to develop a computer based lighting design tool, called the Dynamic Lighting System (DLS), which: -

- can predict varying illumination by both natural and artificial light, under realistic sky conditions over long periods of time
- can predict the electrical energy consumption of artificial lights controlled by lighting control systems

This thesis, and the computer program it describes, are intended to provide architects and lighting engineers with the ability to quantitatively evaluate the dynamic behaviour of complex lighting designs incorporating both natural light and artificial light controlled by a lighting control system.

1.5 Research methodology and thesis content

This thesis describes the development of the DLS. In Chapter 2 , established methods used for calculating illumination are discussed, and the motivation for the development of a new lighting design tool is described. The theoretical basis for the techniques used in the DLS is described in Chapter 3 . Chapter 4 provides an overview of the DLS program. In Chapters 5 and 6 , the major elements of the program, and the data processing techniques used are described in more detail. In Chapter 7 , simulation results obtained using the DLS are compared with illumination measured inside a real building under realistic conditions. Chapter 8 describes the conclusions resulting from this research. In Appendix A, the mathematical equations used in the processes described in Chapters 5 and 6 , are described in more detail. Appendix B provides a systematic illustration of the lighting design process using the DLS, from the inputting of building geometry, through the specification of luminaires and the points at which illumination is to be measured, to obtaining illumination predictions. The programming language chosen to write the DLS (Java) is described in Appendix C. A CD-ROM containing the DLS Java source code and HTML documents that show the classes and their properties and methods, is included at the back of the thesis.

Chapter

2 Background

2.1 Introduction

This chapter describes the two sources of illumination available to building designers, natural light and artificial light, and some of the techniques used to estimate levels of internal illumination.

The chapter begins by describing natural light and some of the techniques used by designers to estimate levels of natural illumination. These techniques, based on the calculation of Daylight Factors, estimate the level of illumination from a standard overcast sky. They are not suitable for estimating illumination from less uniform (more realistic) sky conditions and those that include direct sunlight.

The chapter continues by describing techniques for estimating illumination by artificial lights. Techniques for estimating direct and indirect illumination are described, and a technique for estimating the illumination from groups of lights arranged in a regular pattern.

The techniques described in this chapter are only suitable for estimating illumination under static conditions. They are not suitable for estimating realistic time-varying natural illumination and illumination from artificial lights controlled by an automatic lighting control system. The chapter concludes by describing the requirements for a lighting design tool, the Dynamic Lighting System (DLS), which addresses these limitations.

2.2 Illumination by natural light

Natural light is both free and non-polluting. It can also be visually stimulating; one common criticism of spaces lit wholly or predominantly by artificial light is that the uniformity of the illumination is perceived as dull. Natural illumination through windows can also provide a sense of connection with the external environment, reducing a sense of confinement or claustrophobia.

However, there are some disadvantages with natural illumination. For example, natural light is not available for 24 hours of the day, and even during daytime, levels of illumination can vary considerably. It is often not possible to use natural light to provide adequate illumination in all areas of a building. Where natural illumination is practical, it can cause glare and excessive visual contrast, particularly close to windows. In addition, direct sunlight can have an unwanted heating effect.

Although the use of natural illumination is clearly desirable, good lighting design that incorporates a high proportion of natural light is by no means easy to achieve.

2.2.1 Estimating internal natural illumination

Most techniques for evaluating the potential of a building design to provide adequate internal levels of illumination using natural light are based on the calculation of Daylight Factors. A Daylight Factor is the ratio of internal illuminance to unobstructed external illuminance on a horizontal plane from a non-directional CIE[1] overcast sky [CIE 55], expressed as a percentage.

Design criteria seek to ensure that adequate Daylight Factors are provided where necessary (usually on the working plane) and that the variation is not too great. Daylight factors are easy to calculate, and a variety of techniques are available.

2.2.1.1 Paper-based techniques

Several paper-based techniques can be used to calculate Daylight Factors. These techniques calculate three components of illuminance: -

i. the Sky Component (SC), light direct from the sky vault

ii. the Externally Reflected Component (ERC), light reflected from external obstructions such as other buildings

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[1] Commission Internationale de l'Éclairage

iii. the Internally Reflected Component (IRC), light reflected off internal surfaces

The Daylight Factor is the sum of these three components, multiplied by compensation factors for glazing type, window framing and window dirt.

$$Daylight\ Factor = (SC + ERC + IRC) \times C_1 \times C_2 \times C_3 \qquad \textbf{(2-1)}$$

where C_1 = correction factor for glazing type

C_2 = correction factor for window framing

C_3 = correction factor for window dirt

One of these techniques uses the Building Research Station (BRS) Daylight Protractor and BRS Nomogram [Smith 82]. The BRS Protractor is used in conjunction with a plan (Figure 2.2) and elevation (Figure 2.2) of the room to calculate SC and ERC. The SC value for a window of infinite length, which corresponds to the angle subtended by the visible sky, is measured on the room elevation. This is multiplied by a correction factor corresponding to the width of the window, which relates the angle subtended by the sides of the window, measured on the room plan, to the average angle of elevation of the sky component. The ERC value is calculated in the same way then multiplied by a correction factor to account for the reduced level of light after reflection.

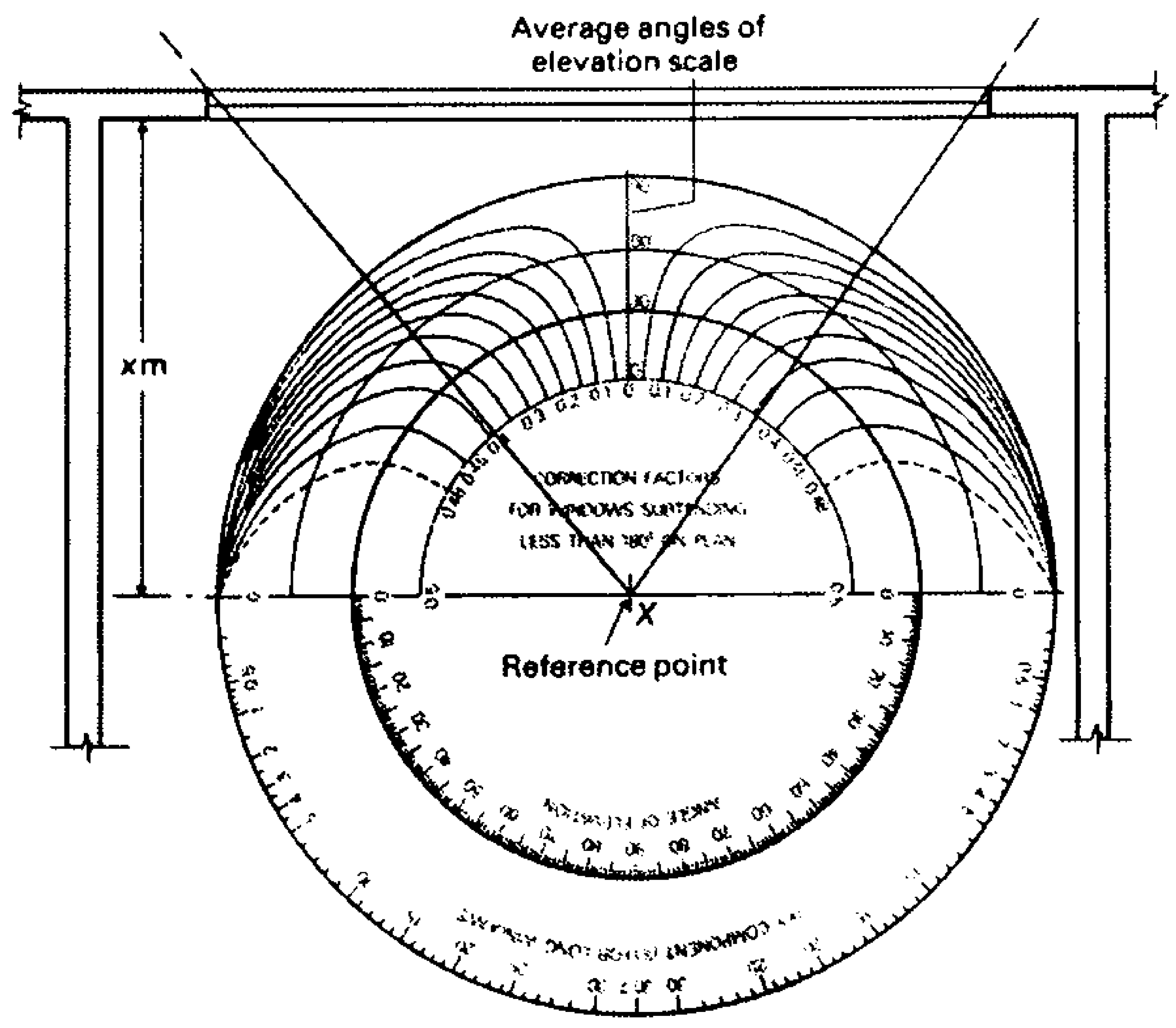

Figure 2.1 The BRS Daylight Protractor, used to measure the angle subtended by the sky and any external obstructions visible through a window on the plan view.

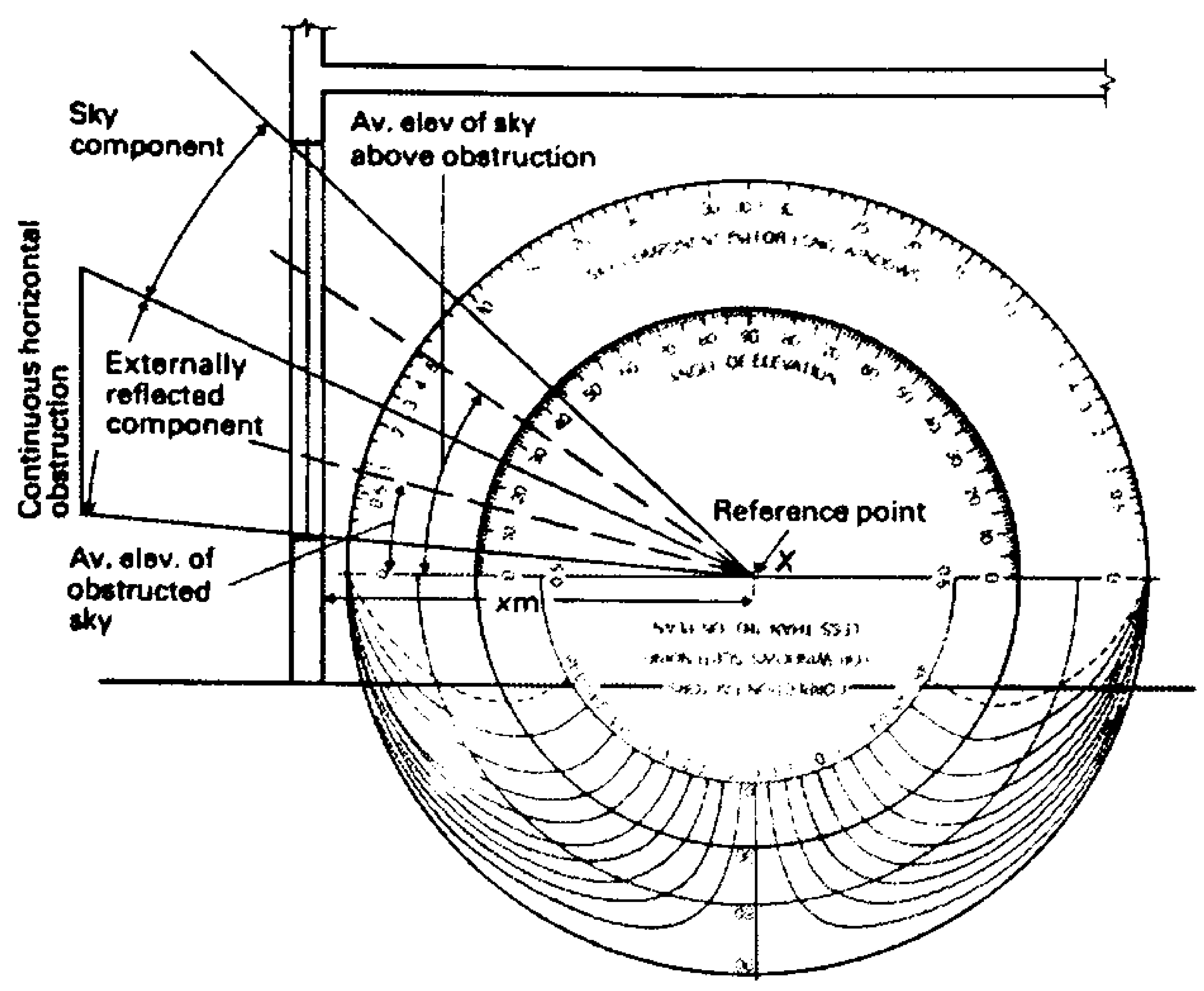

Figure 2.2 The BRS Daylight Protractor, used to measure the angle subtended by the sky and any external obstructions visible through a window on an elevation view.

The BRS Nomogram (Figure 2.3) is used to calculate the average Internally Reflected Component (IRC). A line is drawn connecting the ratio of the area of the window to the total surface area of the room on scale **A** with the average reflectance of all the surfaces on scale **B**. The point at which this line intersects scale **C** gives the value of IRC without external obstructions. If there are external obstructions, a second line is drawn from the average elevation of the obstructed sky, passing through the value of unobstructed IRC on scale **C**. The point at which this line intersects scale **E** gives the value of IRC when part of the sky is obstructed.

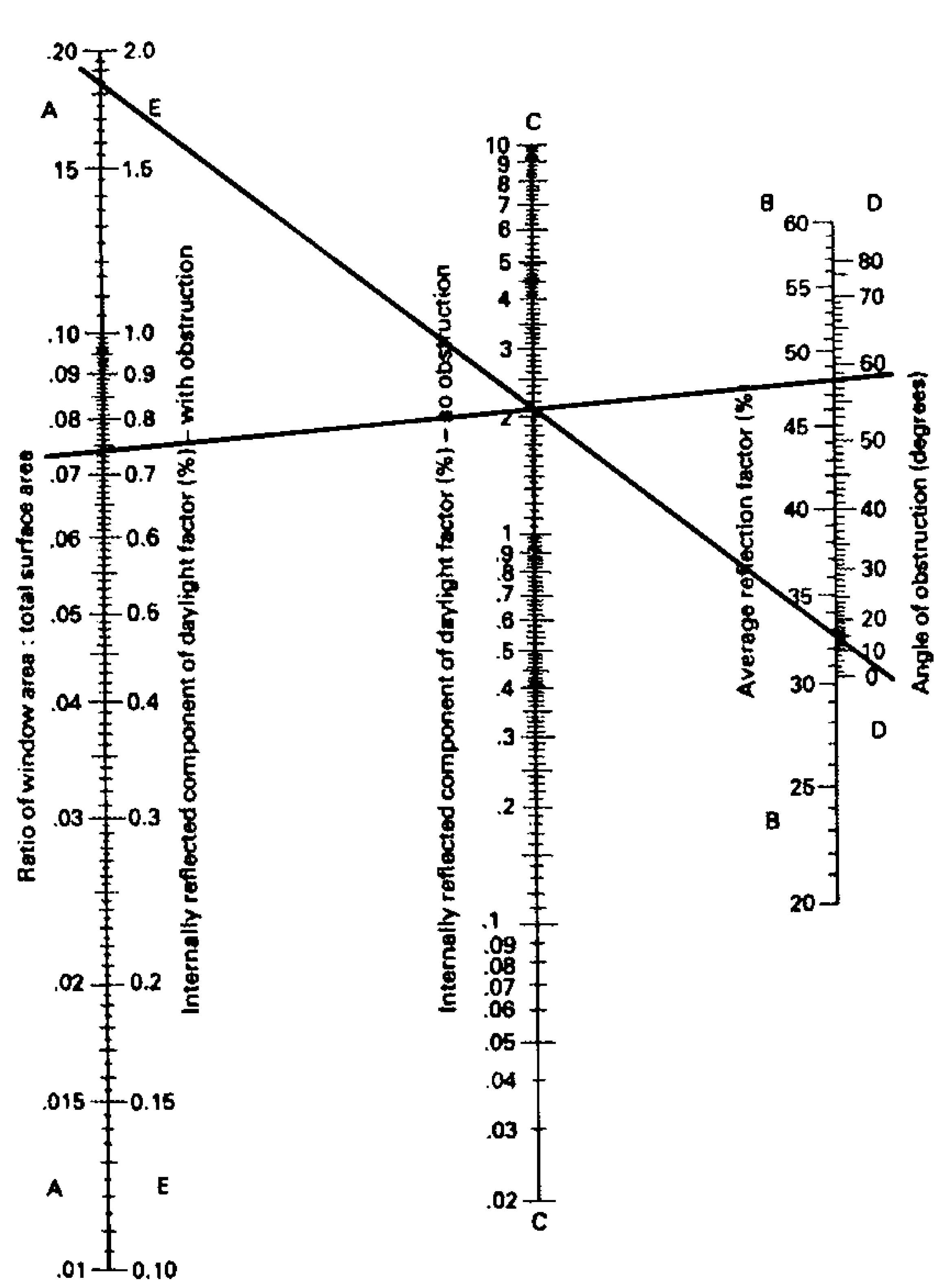

Figure 2.3 The BRS Nomogram is used calculate average Internally Reflected Component

2.2.1.2 Scale models and an artificial sky

Daylight factors can also be estimated using scale models illuminated by an artificial sky. There are two types of artificial sky. The most common type is a small room, lit from above, with mirrors on all sides to create the effect of an infinite horizon. The brightness of the lights is set to represent the luminance distribution of a standard CIE overcast sky. The other type of artificial sky is a dome with lights fitted to the interior surface. The brightness of each light can be adjusted to enable a range of different luminance distributions to be modelled.

A scale model, constructed with accurately modelled openings and surfaces that correctly simulate the reflectance of internal surfaces, is placed at the centre of the artificial sky. Illuminance values are measured at points within the model using a calibrated photocell. The daylight factor is the ratio of an illuminance value measured inside the model to an illuminance value measured from the entire artificial sky, with the model removed.

This technique has the advantage that it is simple to use and that the different components of illuminance do not need to be calculated separately; they are an integral part of every measurement. It can however, be difficult and costly to accurately model complex building geometries, and artificial skies are relatively large and expensive. The type of artificial sky constructed from mirrors is limited to modelling the CIE overcast sky distribution. The dome type is limited in the accuracy with which patterns of distribution can be modelled because it is constructed using lights of finite size that do not cover the whole dome surface. It is also not able to model the full range luminance that a real sky can produce.

2.2.1.3 Computer modelling

There are computer programs that implement analytical methods of calculating daylight factors. Programs such as the Daylight Program [Frame 91] can be used to calculate daylight factors for simple rectangular rooms with windows and or rooflights. Daylight factor values are calculated at points within the space and presented as either numeric values or contours plots. Although the program limits the complexity of building geometry that can be modelled, it is simple to use and requires only a low specification personal computer (PC) on which to run.

2.2.2 Limitations of the Daylight Factor approach

The standard CIE overcast sky model, used to calculate Daylight factors, corresponds to only a small proportion of actual real sky conditions. In northern Europe, an overcast sky only roughly matches approximately 40% of actual sky conditions. In many other sunnier parts of the world, overcast conditions are much less common. This poor correspondence makes daylight factors unsuitable for evaluating the effectiveness of a lighting design over time and in many sunny locations. Ideally, therefore, daylight design must take into account realistic sky and sun conditions and seasonal variations.

The daylight factor techniques, and the calculation methods based on it, are also unable to evaluate designs that combine natural light with artificial lights controlled by a lighting control system. These are dependant on the time-varying characteristics of daylight and sunlight, with the added complexity of time-varying artificial lights and feedback loops to a lighting control system.

In addition, the overcast sky model does not model the directional properties of real sky conditions, for example the presence of a bright circumsolar region, or the contribution from direct sunlight. This makes it unsuitable for evaluating designs that make significant use of shading or redirection devices, for example external shading, light shelves and some atria, because these primarily either block or redirect direct sunlight.

2.2.3 Computer simulation

Computer simulation is growing in popularity due to its greater flexibility. Although originally developed for rendering images, radiosity and ray-tracing techniques can also be used to calculate daylight factors and to calculate levels of illumination at specific points within a space.

2.2.3.1 Radiosity

Radiosity techniques developed for image rendering and lighting simulation are based on thermal-engineering models for emission, reflection and absorption of thermal radiation. The method assumes the conservation of light energy in a closed environment; all energy emitted or reflected by each surface is accounted for by its reflection or absorption by all other surfaces. Surfaces are sub-divided into small patches and the relationship between each patch and every other patch calculated.

The basic radiosity algorithms used in programs such as SUPERLITE [King 96] model materials as diffuse reflecting surfaces. Radiosity techniques can be extended to model some specular reflection by sub-dividing the solid angle subtended by each patch when viewed from the others. However, this approach is unable to accurately model the full range of reflectance characteristics and adds substantially to the amount of information that must be computed. This limits the usefulness of radiosity for modelling situations that include materials with a significant specular reflectance component, or materials that refract light such as innovative glazing materials.

Radiosity is particularly suitable for visualisation where multiple viewpoints are required, such as animation sequences, because the pre-computed relationships between surfaces are independent of viewpoint. Visualisation programs such as Lightscape [Autodesk 99] use ray-tracing techniques to add the visual appearance of specular reflections to an image rendered using radiosity. However, ray tracing is only used to add additional visual information, it does not contribute to the illuminance calculations.

2.2.3.2 Ray Tracing

Ray tracing techniques were also originally developed for rendering images. The path of light rays is traced from the 'virtual camera' position through each pixel in the image plane (computer screen) and tested to see if the rays intersect surfaces in the scene. If a ray does intersect a surface, the pixel is assigned a brightness and colour corresponding to the surface colour, the surface texture, and the illumination at the point of intersection. In order to determine the illumination, a new set of rays is spawned at the intersection point to establish where the light illuminating that point originated. The process is repeated until a ray intersects a light source or until a maximum number of bounces has been reached. Rays that intersect a light source return the luminous output of the source in the direction of the ray, rays that do not return a default ambient value. When summing the light travelling back along all the rays, the reflective characteristics of the surfaces and angles of incidence are used to weight the contribution from each of the spawned rays. Complex reflectance models can be employed to accurately represent the reflectance characteristics of real materials.

This technique is usually referred to as backward ray tracing, because the path of light rays is traced from the viewpoint back to the sources of light, the opposite direction to which rays of light actually travel. Backward ray tracing is able to model shadows, specular reflections and refractive transparency effects. However, it can perform poorly under some circumstances, for example when tracing paths within objects that contain many inter-reflection paths, such as within complex luminaires or some innovative glazing materials. It has been suggested that forward ray tracing, tracing the path of rays travelling away from the light source, could be used to determine the light output distribution of such objects. When the backward ray-tracing algorithm encounters such an object, this distribution could be used to determine the luminous output back along the path of the ray. Although potentially useful for solving such problems, forward ray tracing is not considered suitable for rendering images because when the paths of rays travelling away from light sources are traced too few rays are likely to pass through the image plane to form an acceptable image.

2.2.3.3 Calculating illumination levels

Radiosity techniques can be used to calculate levels of illumination. However, the limited capacity of the radiosity method to model specular reflection makes it unsuitable for calculating illumination levels in spaces that include materials that have significant specular reflection characteristics. Furthermore, no work has so far been undertaken to validate the application of radiosity techniques to the calculation of natural illuminance values under real sky conditions.

Ray tracing techniques can also be used to calculate levels of illumination, by placing the viewpoint at a point of interest. Rays are spawned in a hemispherical pattern centred on the view direction and the incoming light integrated to calculate the value of illuminance at that point. The backward ray-tracing program RADIANCE [Ward 94] is widely used in lighting design where numerical accuracy is required. RADIANCE overcomes the problem of multiple inter-reflections within luminaires by making use of manufacturers measured photometric data to define the light output distribution rather than calculating is using ray tracing. Measured transmission characteristics could be used in a similar way to model innovative glazing materials. RADIANCE had been validated for numerical accuracy when calculating levels of natural illuminance under real sky conditions [Mardaljevic 95].

2.3 Illumination by artificial lights

Artificial lights can be used to illuminate the interior of a building at times and in places where natural illumination is either inadequate or not available. They can be used to illuminate spaces where a minimum level of illumination must be maintained for safety reasons, such as in a stair well.

However, artificial lights have disadvantages. For example, they consume electrical energy and can produce unwanted heat. The relatively low range of illumination levels produced can lead to a perception of uniformity, and a lack of sensory variety. Certain types of artificial light, such as fluorescent tubes equipped with conventional control gear operating at 50 Hz, can be perceived to flicker. Some people find this characteristic uncomfortable.

2.3.1 Estimating illumination by artificial lights

The light illuminating a surface has two components; a direct component, light that travels directly from the luminaire to the surface, and an indirect component, light that has been reflected off other surfaces. These two components can be calculated. The direct component is proportional to the luminous intensity of the light source, the distance from the source to the point of interest and the angle of incidence of the light striking the surface. The luminous intensity of luminaires is published by the manufacturers. However, the luminous intensity is not usually the same in all directions, therefore manufacturers also publish polar curves that define the luminous intensity distribution. From this the luminous intensity in a given direction can be calculated. As light travels from the source to the point of interest it spreads out, the resulting illuminance decreases in proportion to the square of the distance travelled. The resulting illuminance is also reduced if it strikes the surface with an incident angle of less than 90^0. Direct illuminance E is given by [Smith 82]:

$$E = \frac{I}{d^2} Cos\theta \quad lux \tag{2-2}$$

where I = intensity of the source in the direction of the surface (cd)

d = distance from the source to the surface (m)

θ = angle of incidence, the angle between the direction of the rays of light and the surface normal

This calculation assumes that the luminaire is a point source.

The average value of indirect illuminance on the working plane is proportional to the luminous intensity and the intensity distribution of the luminaire, the reflecting characteristics of the rooms surfaces and their total area. Average indirect illuminance E_{ind} is given by [Smith 82]:

$$E_{ind} = \frac{(F_u \times \rho_u) + (F_d \times \rho_d)}{A(1-\rho)} \quad lux \tag{2-3}$$

where F_u = luminous flux emitted upwards from the luminaire (lm).

ρ_u = average reflectance of the room surfaces above the plane of the luminaire.

F_d = luminous flux emitted downwards from the luminaire (lm).

ρ_d = average reflectance of the room surfaces below the plane of the luminaire.

ρ = average reflectance of all the room surfaces.

A = total area of all the room surfaces (m^2).

In non-domestic buildings, it is often necessary to quantify the number, type and position of luminaires required to achieve a given level of illumination. The Lumen Method can be used to calculate the average illuminance level for square or rectangular rooms fitted with a regular, evenly spaced, pattern of luminaires of the same type. This method accounts for both the direct and indirect components in the one calculation. The average illuminance E_{av} is given by [Smith 82]:

$$E_{av} = \frac{n \times F \times UF \times MF}{A} \quad lux \tag{2-4}$$

where n = number of luminaires.

F = lighting design lumens per lamp, the average luminous output over the life of the lamp.

UF = utilisation factor, the relationship between the luminous output of the lamp and illuminance on the working plane.

MF = maintenance factor, an allowance for dirt and ageing.

A = area of the working plane, usually the floor area.

Simple computer programs based on the Lumen method are provided by luminaire manufacturers to perform this calculation.

2.3.2 Lighting control systems

Where artificial lighting is used to supplement natural light, energy efficiency can potentially be improved by the use of a lighting control system. A sensor measures the overall level of illumination and lights are turned on or off or dimmed automatically to maintain the desired level of illumination. The occupants of a building can however, find automatic lighting control disturbing. Whilst most people do not mind lights being turned on automatically, they often object to them being turned off automatically. One solution to this problem is to restrict the time when they are switched off to periods when the space is largely unoccupied, for example during a lunch break or at the end of the working day.

2.4 Requirements of the DLS

The techniques described in this chapter estimate illumination under static conditions. What is difficult is to quantify the time-varying characteristics, i.e. the levels of illumination and electrical energy consumption, of a lighting design that combines natural light with artificial lights controlled by a lighting control system. An approach is therefore needed that can model realistic conditions and that can incorporate modern design features. A lighting design tool is therefore needed that: -

- can evaluate the time-varying performance of a lighting design, combining natural illumination and artificial illumination
- places no theoretical limit on the complexity of the building geometry, or any external structures
- models the reflective characteristics of material surfaces, including specular reflections, to enable light re-directing devices to be included in the design
- determines the illuminance at any point in the building, on any surface, at any time of day, and on any day of the year, for a given lighting design
- allows the building to be located anywhere in the world, with any orientation
- provides realistic model of sky luminance distributions, from overcast through intermediate to clear sky conditions
- models the full range of natural illuminance, including sunlight as well as daylight
- uses locally measured weather data to control the characteristics of natural light, to more closely replicate local conditions
- models the pattern of light distribution from luminaires realistically
- models a range of lighting control systems, including typical manual switching
- predicts the electrical energy consumption by artificial lights, over any period
- is low-cost and requires only readily available resources to operate
- can be used with the skills usually found in a lighting design or building services engineering office

- produces readily understandable results quickly

This thesis describes the development of a computer-based system that meets these criteria.

2.5 Summary

Most current design techniques used to evaluate the provision of natural illumination are based on the calculation of Daylight Factors. This approach only evaluates the effectiveness of the design under overcast sky conditions. To include the effect of sunlight, more sophisticated techniques must be employed. In addition, the methods used for calculating levels of both natural and artificial illumination are only applicable to static conditions. A technique is therefore required that examines how natural illumination varies with time, and how the control of artificial illumination can be incorporated into the design. The requirements for a new lighting design tool that address these issues have been outlined.

Chapter

3 Theoretical basis for the DLS

3.1 Introduction

For computer modelling to be applied to the calculation of time-varying illuminance over long periods, a technique must be employed that enables illuminance values to be calculated quickly. This chapter begins by describing the theoretical basis of daylight coefficients; the method used by the DLS to calculate illuminance due to daylight for arbitrary sky conditions. An advanced ray-tracing program RADIANCE is then introduced, which is used by the DLS to calculate individual illuminance values, which are in turn used to calculate daylight coefficients. This is followed by a description of the backward ray-tracing algorithm used by RADIANCE. Finally, a method of calculating daylight coefficients using RADIANCE, based on previous research, is outlined.

3.2 Daylight Coefficients

3.2.1 Definition of the daylight coefficient approach

The method used by the DLS to predict illuminance is based on the daylight coefficient approach developed by Tregenza and Waters [Tregenza 83]. This method divides the sky hemisphere into a series of small patches. The fixed numeric relationship between the luminous intensity of each patch of sky and the illuminance from that patch at a measurement point is referred to as a daylight coefficient. The relationship between a patch of sky and the illuminance resulting from that patch is illustrated in Figure 3.1.

Coefficients can be determined by measurement using a scale model under an artificial sky, or calculated by using computer modelling. Once coefficients have been determined for the complete sky hemisphere, the illuminance due to daylight, i.e. light from the sky excluding light from the sun, resulting from any pattern of sky luminance distribution can be quickly calculated. A realistic luminous intensity value is assigned to each patch of sky and the contribution from all patches summed, scaled by the corresponding coefficients.

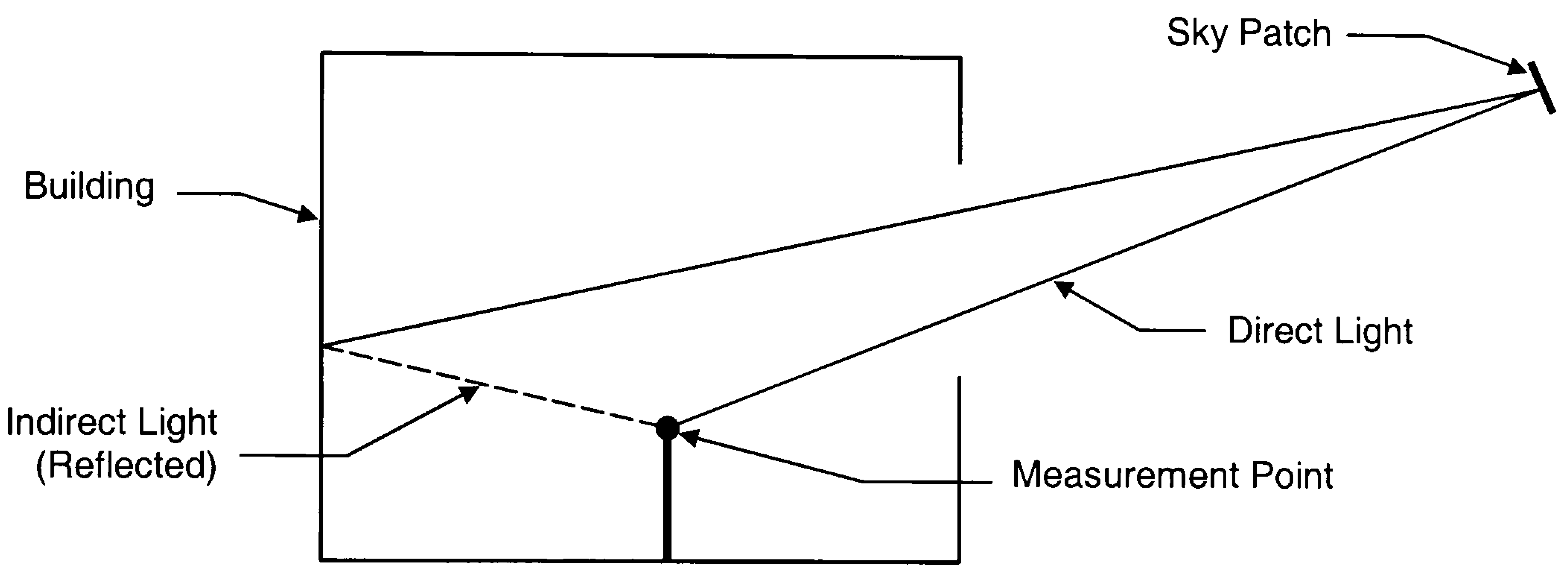

Figure 3.1 Illuminance from a patch of sky

A daylight coefficient value corresponds directly to the geometric relationship between the patch of sky and the measurement point inside the building. If the geometry is altered in any way, the coefficient value will be different. The daylight coefficient approach is therefore not ideally suited to modelling circumstances where the geometry is likely to change. One obvious example is the inclusion of movable blinds. To fully model a space that included movable blinds using daylight coefficients a separate set of coefficients would have to be calculated to every possible position in which the blinds could be placed. In practice, a finite number of positions would be modelled.

3.2.2 Mathematical basis of the daylight coefficient approach

The total illuminance (E) from a hemispherical sky, produced at the measurement point, can be found by

$$E = \int_0^{2\pi} \int_0^{\pi/2} D_{\gamma\alpha} L_{\gamma\alpha} \cos\gamma \, d\gamma \, d\alpha. \qquad \textbf{(3-1)}$$

where $D_{\gamma\alpha}$ is the daylight coefficient and $L_{\gamma\alpha}$ is the luminous intensity of a point on the sky hemisphere at altitude γ and azimuth α.

This continuous function can be approximated by dividing the sky hemisphere into finite patches (p), and summing the illuminance from those patches.

$$E = \sum_{p=1}^{n} D_P S_p L_p \qquad \textbf{(3-2)}$$

where D_p is the daylight coefficient, S_p the solid angle and L_p the luminous intensity of patch p.

A daylight coefficient for a patch of sky, at altitude γ and azimuth α, is defined as

$$D_{\gamma\alpha} = \frac{\Delta E_{\gamma\alpha}}{L_{\gamma\alpha} \Delta S_{\gamma\alpha}} \qquad \textbf{(3-3)}$$

where $L_{\gamma\alpha}$ is the luminance of the patch, $\Delta S_{\gamma\alpha}$ is the patch solid angle and $\Delta E_{\gamma\alpha}$ is the resulting illuminance.

3.2.3 Calculating daylight coefficients

Computer simulation can be used to calculate daylight coefficients, by including a single patch of sky in a simulation and calculating the resulting illuminance at points of interest within a space. A daylight coefficient is the ratio of the luminance of the patch to the resulting illuminance.

Radiosity can be used to calculate daylight coefficients by repeated simulation, including a self-luminous external patch of sky in each simulation [Tregenza 94]. This method is limited by the inability of radiosity to accurately model surface reflectance characteristics, as described in section 2.2.3.

Backward ray tracing can also be used to calculate daylight coefficients by repeated simulation, including a single patch of sky in each simulation [EPSRC 97, Cropper 97]. The ray-tracing program RADIANCE is able to model the full range of surface reflectance characteristics. Furthermore, the numerical accuracy of the calculation of illuminance values using daylight coefficients calculate using RADIANCE has been validated by comparing predicted values with values measured under test conditions [Mardaljevic 98].

3.3 Calculating illuminance using RADIANCE

RADIANCE [Ward 94] is an advanced physically based ray-tracing program that can be used to predict illuminance in buildings. RADIANCE is capable of calculating complex inter-reflections, and places no theoretical limitation on the complexity of the building geometry. Previous research has validated the general numerical accuracy of RADIANCE [Grynberg 89], and for calculating illuminance values under real skies [Mardaljevic 95].

RADIANCE uses recursive backward ray tracing, illustrated in Figure 2.2, to calculate illuminance at a point on an imaginary plane by integrating incoming rays of light, in a hemisphere normal to the plane. Multiple light paths are examined by directing rays away from the measurement point, and calculating how much light will arrive along those paths. If a ray hits a source of light, the amount of light emitted along the direction of the ray is used in the calculation. If a ray hits a surface, a further sampling is initiated at that point to calculate inter-reflected light. When this new calculation is completed, the amount of light emitted along the original path is determined from the illuminance at the point and the reflective characteristics of the surface. This process is repeated until a pre-determined number of reflections (bounces) have been reached. After each reflection, the number of rays used in the calculation is reduced. This is possible because the contribution to the overall calculation reduces each time light is reflected. These and other economies are used to reduce the time required to complete the calculations.

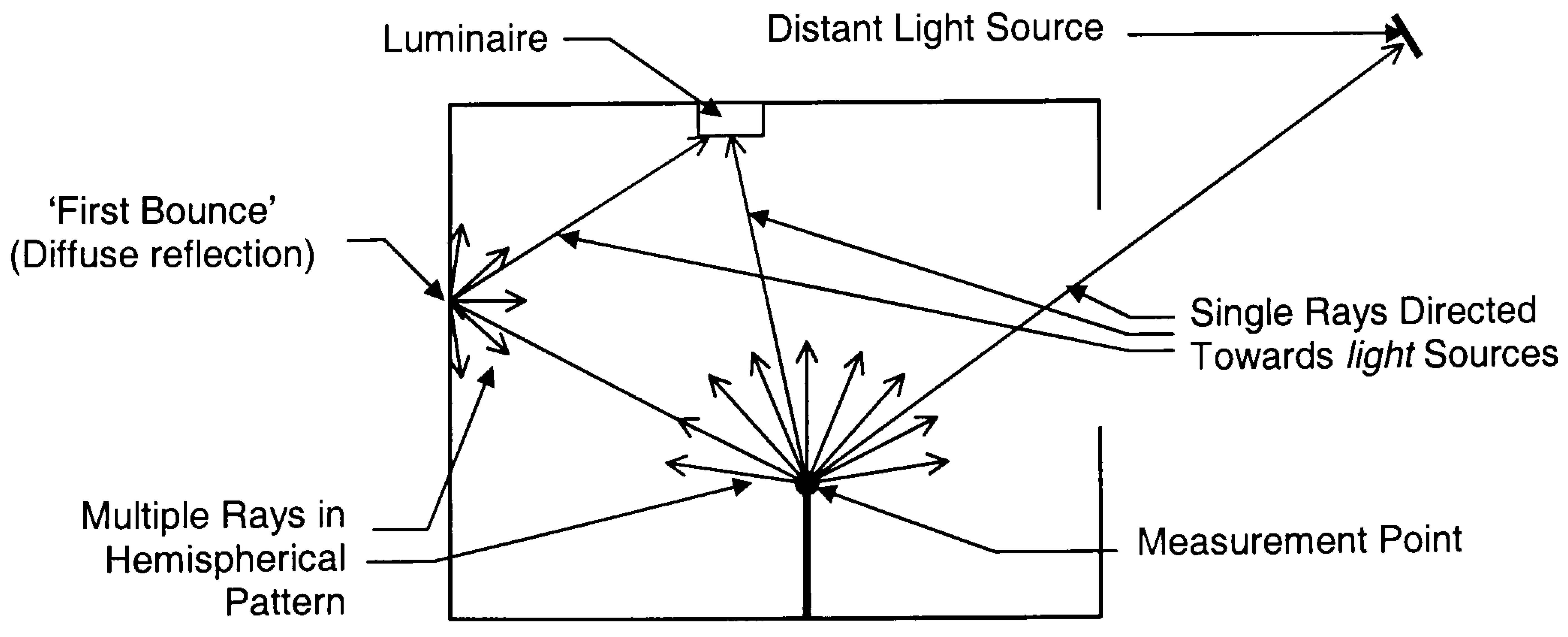

Figure 3.2 Recursive backward ray tracing

RADIANCE provides two types of light source; type *light* and type *glow*. A *light* source is used to define the luminous output of surfaces and of distant light sources, i.e. a source that subtends a small angle. Each time a set of rays is spawned, in addition to the hemispherical pattern of rays, single rays are directed towards the centre of each *light* source. If there is a direct path from the point to the centre of the *light* source, the luminous output of the *light* contributes to the illuminance calculation. A *glow* source is used to define the luminous output of a secondary light sources. A *glow* source contributes to the calculation if one or more of the hemispherical sampling rays hit that surface.

3.4 Calculating daylight coefficients using RADIANCE

Preliminary research into using RADIANCE to calculate daylight coefficients [Mardaljevic 97] was conducted using a specific sky discretisation. Measured data, gathered by the UK Building Research Establishment[1] (BRE), was compared with illuminance predictions calculated using daylight coefficients. A validation data set containing 754 entries was used; covering a wide range of naturally occurring sky conditions, from heavily overcast, through intermediate to clear sky conditions. Each entry in the data set included illuminance values measured in a test room, together with measurements of global horizontal, direct normal and sky luminance distribution. A scanning device was used to measure the sky luminance at 145 positions evenly distributed over the sky hemisphere, every fifteen minutes during daylight hours. To replicate these conditions when calculating daylight coefficients, sky patches were used that matched the size and position of the areas of sky measured by the sky scanner.

The methods used by RADIANCE to calculate illuminance contain many compromises to ensure that the calculations are completed in an acceptable time. When RADIANCE is used to calculate illuminance from a whole sky, these compromises have little effect on the results of the calculations. However, when used to calculate illuminance from a discretised sky, these

[1] Building Research Establishment, Garston, UK.

compromises can produce unacceptable errors. A method must therefore be employed that minimises these errors. Daylight coefficients are divided into two components; a direct component, light arriving directly from the patch of sky; and an indirect component, light arriving after being reflected.

If a sky patch is modelled as a *light* source, RADIANCE will only include a direct component if the centre of the patch is visible from the measurement point. If the patch were partially obscured, such that the centre was not visible, this could result in a significant error, as the direct component would be omitted. If a sky patch is modelled as a *glow* source, RADIANCE may not sample the patch at all, unless a large number of rays are used. If a large number of initial rays are used, when the calculation includes multiple inter-reflections, simulation times can be prohibitive. Different methods are therefore employed to calculate the direct and indirect components.

The direct component is calculated by modelling the sky patch as a *glow* source. A large number of rays are used to ensure that the sky patch is adequately sampled. No inter-reflections are included, significantly reducing the simulation time. The indirect component is calculated by modelling the sky patch as a *light* source. The calculation is divided into two stages. An illuminance value from multiple inter-reflections is first calculated, that may or may not include a direct component. The calculation is then repeated, with no inter-reflections, calculating the direct component only (which may be zero). This value is subtracted from the combined value to yield only the indirect component. The same principle is also applied to calculating light from the sun.

The total natural light at a point, E, is therefore evaluated as the sum of four components of illuminance:

$$E = E^{d} + E^{i} + E^{sd} + E^{si} \tag{3-4}$$

Where E^{d} and E^{i} are, respectively, the direct and indirect components of illumination due to daylight. Similarly, E^{sd} and E^{si} are the direct and indirect components of illumination due to sunlight. The direct components account for window and room configuration, external obstructions and glazing transmittance. The indirect quantities account for the inter-reflected light components, which for both cases, sun and sky, include internal and external reflections.

3.5 Summary

The DLS uses the daylight coefficient approach to enable time-varying illuminance to be calculated quickly. A daylight coefficient is the numeric relationship between the luminance of a patch of sky and the illuminance at a measurement point from that patch. The DLS uses RADIANCE to calculate daylight coefficients. Daylight coefficients can then be used to determine the illuminance at a measurement point resulting from any pattern of sky luminance distribution. Sources of inaccuracy, resulting from the methods employed by RADIANCE, can be reduced by calculating direct and indirect components of illuminance separately.

Chapter

4

Description of the DLS program

4.1 Introduction

This chapter describes the Dynamic Lighting System (DLS) program developed during this research. The chapter begins by describing how the computer platform and programming language used to develop the DLS were chosen, and some of the implications of those decisions.

The major features of the user interface are then described, starting with how the geometry of a building (including any external obstructions) is input into the DLS, and how it is displayed. The method used to specify the type and location of any luminaires is then described, followed by the methods used to define the points at which illuminance is to be calculated.

The chapter concludes by describing how daylight coefficients and artificial light coefficients are calculated, followed by how they are used to predict illuminance due to daylight, sunlight and artificial lights.

4.2 Computer Platform and Programming Language

The DLS uses the ray-tracing program RADIANCE to calculate lighting coefficients. RADIANCE was chosen because of its ability to calculate the full range of illuminance from daylight, sunlight and artificial lights and because of its ability to accurately model reflected light. RADIANCE is actually a collection of programs, only a few of which are needed to calculate coefficients. It was decided to use these programs in their original form rather than to embed RADIANCE code within the DLS. Using the RADIANCE programs unaltered eliminates the risk of introducing errors into the RADIANCE code, and allows users of the DLS to benefit from any improvements subsequently made to RADIANCE.

When this research began, the primary platform for running RADIANCE was a UNIX workstation. A PC version of RADIANCE was available as part of the ADELINE suite of lighting programs [Ehrlich 96]. ADELINE comprises the SCRIBE modeller, a tool for defining building geometry, SUPERLIGHT, a radiosity program for simple daylight calculations and modelling artificial lights, and RADIANCE. This version of RADIANCE, however, was only available in a pre-compiled form designed to run under the MSDOS operating system. It was therefore decided to initially develop the DLS to run on a UNIX workstation, but to ensure that it was suitable to run on PCs should an improved version of RADIANCE become available.

RADIANCE is a very powerful and a very flexible lighting design tool. Much of this flexibility however, is the result of its integration into the UNIX environment. This power and flexibility, and the need to be familiar with UNIX, has tended to restrict the use of RADIANCE to a relatively small number of lighting specialists. One of the design goals therefore, is to design a system that is easy for non-specialists to use, and that does not require a detailed knowledge of UNIX. To achieve this, a Graphical User Interface (GUI) is provided that hides much of the complexity of the processing sequences. The decisions that the DLS should be capable of running on different platforms, and in particular, that it should have a GUI, restricted the choice of programming language.

Interactive computer programs can be considered to comprise two parts; the processing part, the part that performs the main functions of the program, and the user interface, the part that enables the user to interact with the program. Compilers are available for most programming languages and for most platforms, which allow programs written using the standard features of a language to be compiled to run on different platforms. However, features for providing a GUI are often extensions to the standard language and are platform specific. The implications for the design of the DLS are that although the processing elements of the program can be written in any one of a variety of different languages, the availability of GUI libraries compatible with both X Windows (the standard UNIX windowing environment) and Microsoft Windows (the standard PC windowing environment) is much more restricted.

A new language Java, developed by Sun Microsystems, offers a solution to this problem. Java is designed to run on what is termed a 'virtual machine', an interpreter that allows the platform independent Java code to run (unaltered) on the underlying computer architecture. It was decided to develop the DLS using Java, to take advantage of this machine independence.

Java also has some potential disadvantages. The first of these is the speed at which Java programs execute. Java is an interpreted language rather than a compiled language. The Java source code is compiled to an intermediate form, termed 'bytecode', which is subsequently interpreted by the virtual machine. This is much less efficient than compiling to (architecture specific) machine code. However, as the RADIANCE modules, which are written in C, perform most of the computationally intensive processing, they are compiled to machine code. The Java modules however, do not perform computationally intensive tasks and so the speed at which the Java modules execute is not critical.

The second potential disadvantage is that Java is a new language. For the DLS to be a useful tool for lighting designers, it is important that its development can continue after the conclusion of this research. For that to be possible, Java and associated development tools must continue to be available, which depends to some extent on the success of Java as a language. At the time the choice of language was made, it was judged that there was already widespread adoption of Java, and that the risk of it failing was very small. This judgment has subsequently been proved correct; Java is now established as a major programming language.

One of the consequences of Java being a relatively new language was the limited availability, initially, of sophisticated features. The most significant deficiency during the early development of the DLS was the lack of support for displaying three-dimensional (3D) objects. This necessitated the writing of a '3D viewer' to enable building geometry to be displayed. A comprehensive 3D class library has subsequently been added to Java, although the DLS does not currently make use of it.

The Java programming language is described in more detail in Appendix C .

4.3 Building Geometry and Surface Properties

Building geometry is defined using the standard RADIANCE input format. When a file has been loaded, the DLS displays a wire-frame representation of the building geometry, defined by polygons. In addition to polygons, RADIANCE supports the following geometric shapes; sphere, cone, cylinder and ring, but only polygons can be displayed. However, as no alteration is made to the geometry files, which are used as direct input to RADIANCE modules, any of the other RADIANCE geometric shapes can be included in the geometry files. These geometry files also contain information about the colour, reflectivity, roughness and specularity of surfaces and the transmission properties of glazing materials.

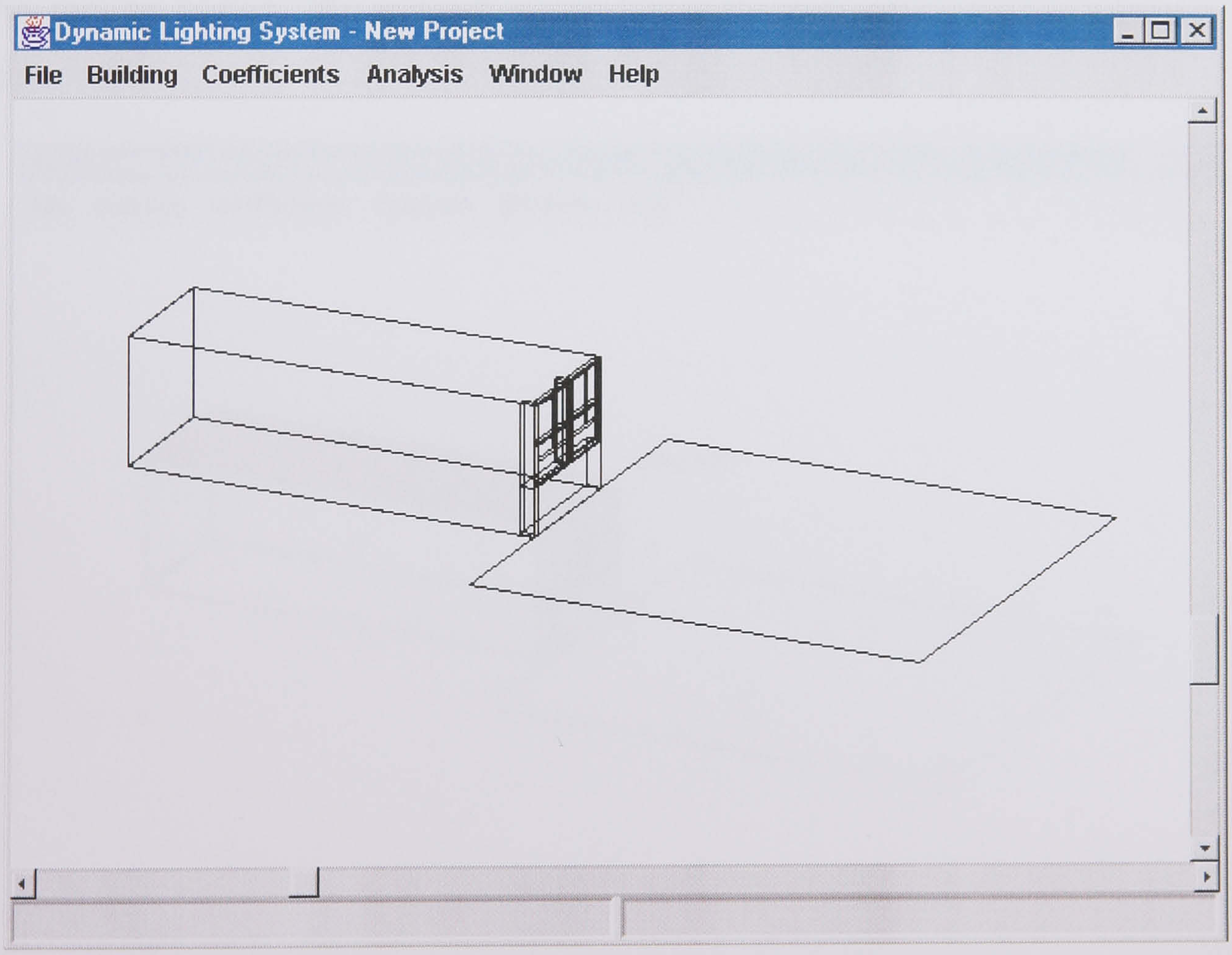

Figure 4.1 Wire-frame view of building geometry

The display of an office space and its foreground is illustrated in Figure 4.1. The users are able to rotate the wire-frame image to view the building from any direction, enlarged or reduced and move it around within the viewing window.

4.4 Artificial lights

The DLS includes a database of luminaires, described in Section 5.3.2. A grid of luminaires is positioned in the building relative to any surface polygon, selected by the user in the wire-frame view using the mouse. Figure 4.2 shows a wire-frame view of a room with the polygon representing the ceiling highlighted. Repeated selection of a polygon highlights each side in turn, indicated by a change in colour. The side of the polygon on which the luminaires will be placed is indicated by a bright red colour. A dark red colour indicates that the luminaires will be placed on the opposite side. When the mouse pointer lies inside more than one polygon, each time the user clicks the mouse button, the system cycles through each side of each polygon in turn.

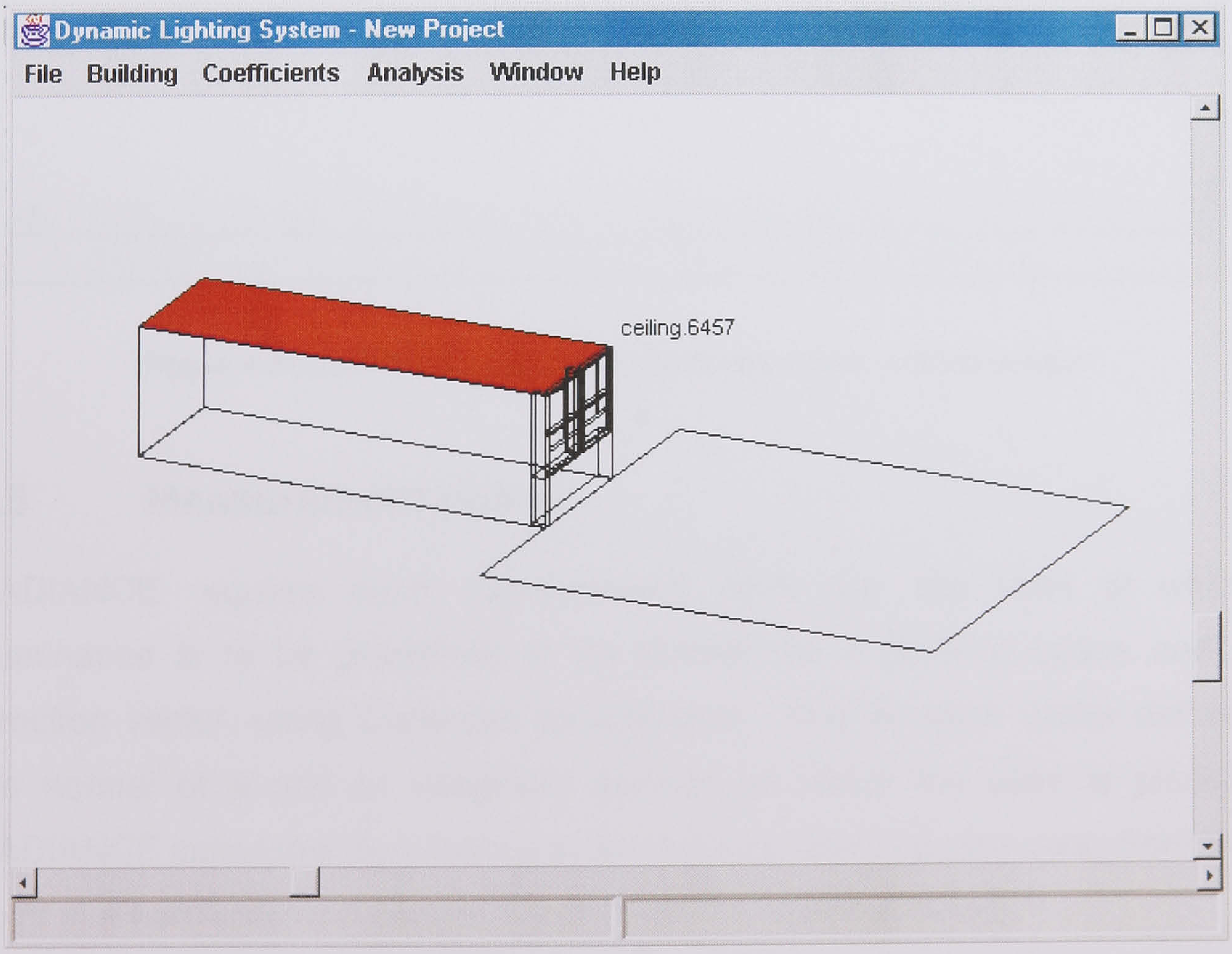

Figure 4.2 A polygon used to locate luminaires, highlighted in red, is selected using the mouse

Once a surface polygon has been selected, a luminaire type is then chosen from the database and the number of rows and columns of the grid and the spacing from the plane of the polygon are specified. The geometry viewer then shows the position and orientation of the luminaires, a representation of their geometry and an identification number, as illustrated in Figure 4.3.

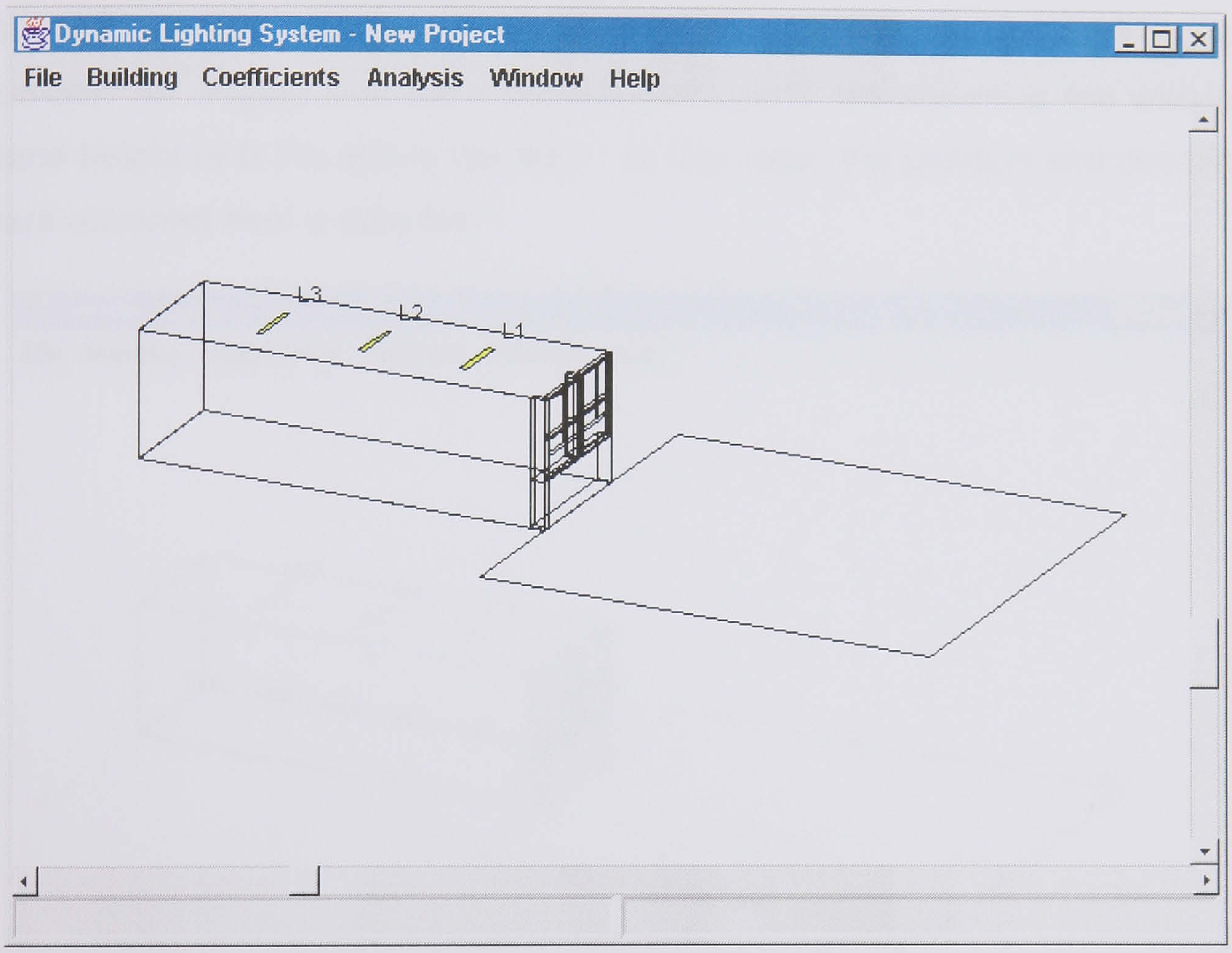

Figure 4.3 Luminaires are shown by geometry viewer as filled polygon

4.5 Measurement points

RADIANCE requires each measurement point (i.e. the point at which illuminance is to be predicted) to be defined as a point in space and a direction vector, using Cartesian co-ordinates. The direction vector defines the normal of a real or imaginary surface on which the point is placed. RADIANCE calculates illuminance at the point by directing rays away from the point in a hemispherical pattern, centred on the direction vector.

The DLS provides two ways to define measurement points, a list of points and directions held in a data file or a grid of points relative to a polygon. A grid of points is defined in a similar way to a grid of luminaires, as described above.

The user first selects a polygon in the wire-frame view, using the mouse. The spacing of the points and the distance of the points away from the plane of the polygon are then specified via a dialogue box.

Points can be positioned anywhere in the scene and have any orientation. Once defined, the geometry viewer shows the position and direction vectors of the measurement points, as a cross with a direction line, and an identification number. In Figure 4.4, the measurement points are shown at the working plane height of 0.7m above the floor. In this case, the position and direction were obtained from a data file.

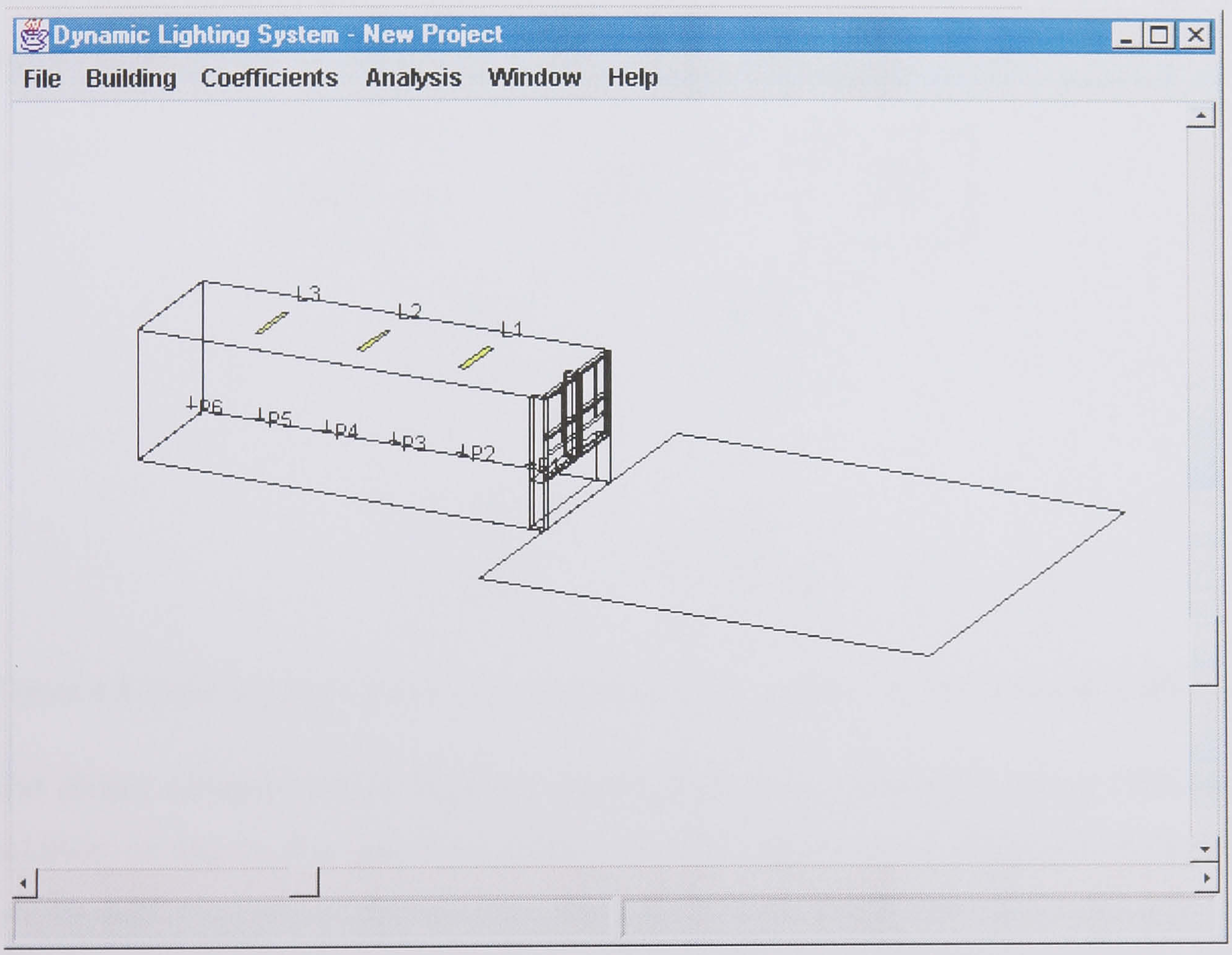

Figure 4.4 Measurement points shown by geometry viewer

4.6 Calculating lighting coefficients

The major elements of the DLS used to calculate lighting coefficients are illustrated in Figure 4.5. The program calculates the indirect component of daylight coefficients by combining individual patches of sky in turn with the building geometry and using RADIANCE to determine how much indirect light arrives at the measurement point. In this research, a generic method of sky discretisation using triangular patches is employed, enabling much higher levels of discretisation to be used than were used in the previous study [Mardaljevic 98]. The method of discretisation used by the DLS, described in chapter 5 , yields a sky hemisphere formed from 40, 160, 640 or 2560 patches. There is no theoretical limit to the number of patches produced by this method, each time the patches are subdivided the number of patches increases by a factor of four. Using a generic method enables different levels of discretisation to be used when calculating the direct and indirect components. If a finer discretisation is used when calculating the direct component, the area of sky visible from the measurement point can be represented more accurately.

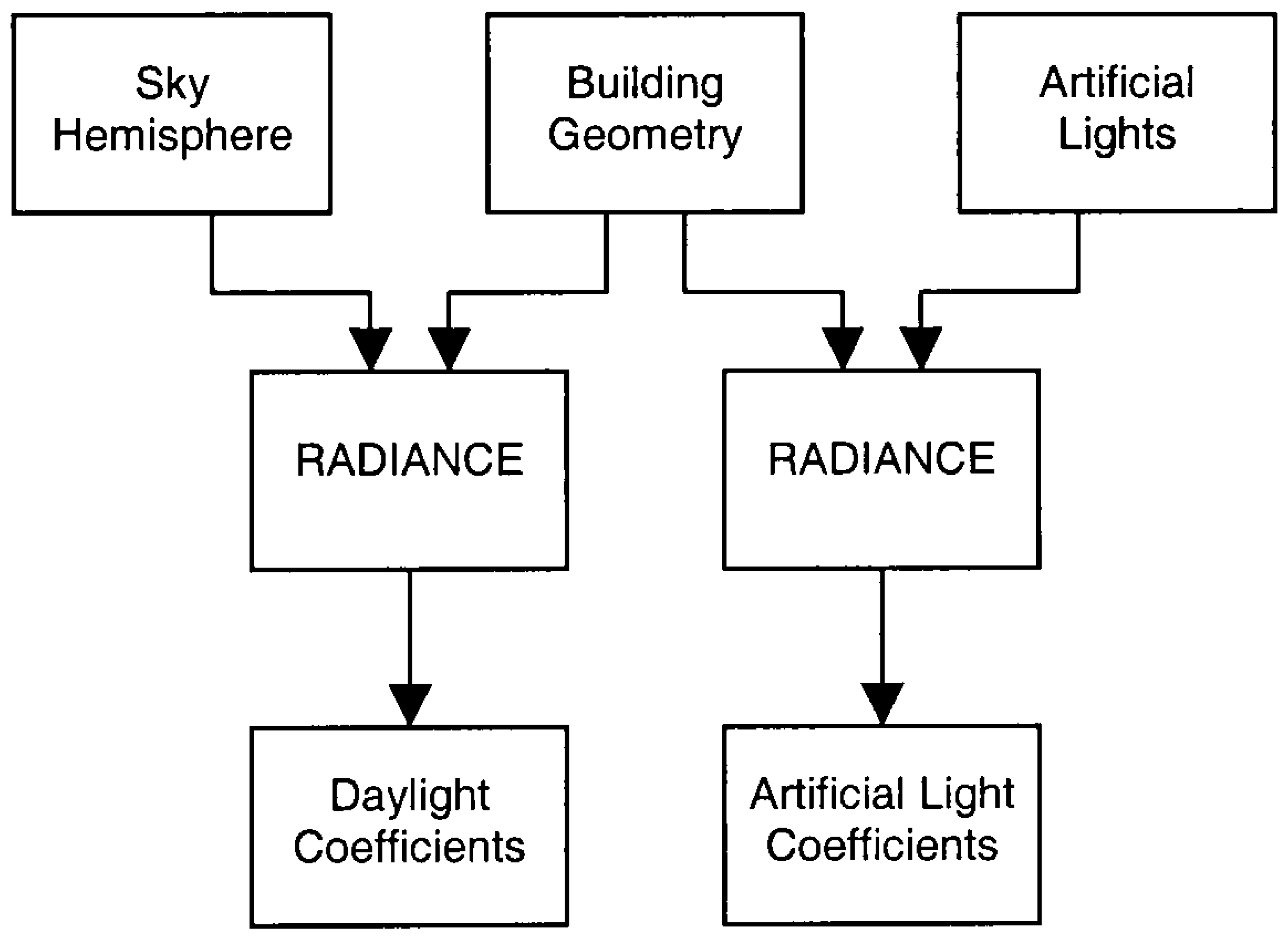

Figure 4.5 Major elements of the DLS used to calculate daylight and artificial light coefficients

The direct component of daylight coefficients was calculated using individual patches of sky in the previous study. In this research, a different method is employed. Using a complete sky modelled as a single light source, rays are directed towards the centres of the patches of an equivalent discretised sky. RADIANCE is used to test if the rays hit the sky hemisphere, and to determine the attenuation due to any participating media such as glass.

In the previous study, sunlight was predicted using coefficients calculated by explicitly positioning a RADIANCE light source at the sun's position at each prediction time. Although this is the most accurate way to calculate sunlight, the coefficients that result correspond to particular instances in time at a specific world location. In this research, the direct and indirect solar components are calculated using the daylight coefficients corresponding to the sky patch that is nearest to the sun's position at the prediction time. Using this approach, the coefficients can be used to predict illuminance at any time and at any location.

Models of luminaires, which can include complex distributions of light output, provide sources of artificial illuminance. The DLS program calculates artificial light coefficients by combining each luminaire model in turn with the building geometry and then uses RADIANCE to determine how much artificial light arrives at the measurement points.

The calculation of coefficients is performed only once for a given building geometry and lighting layout. The methods used to calculate daylight coefficients and artificial light coefficients are described in more detail in chapter 6 .

4.7 Predicting illuminance

The major elements of the DLS used to predict illuminance are illustrated in Figure 4.6.

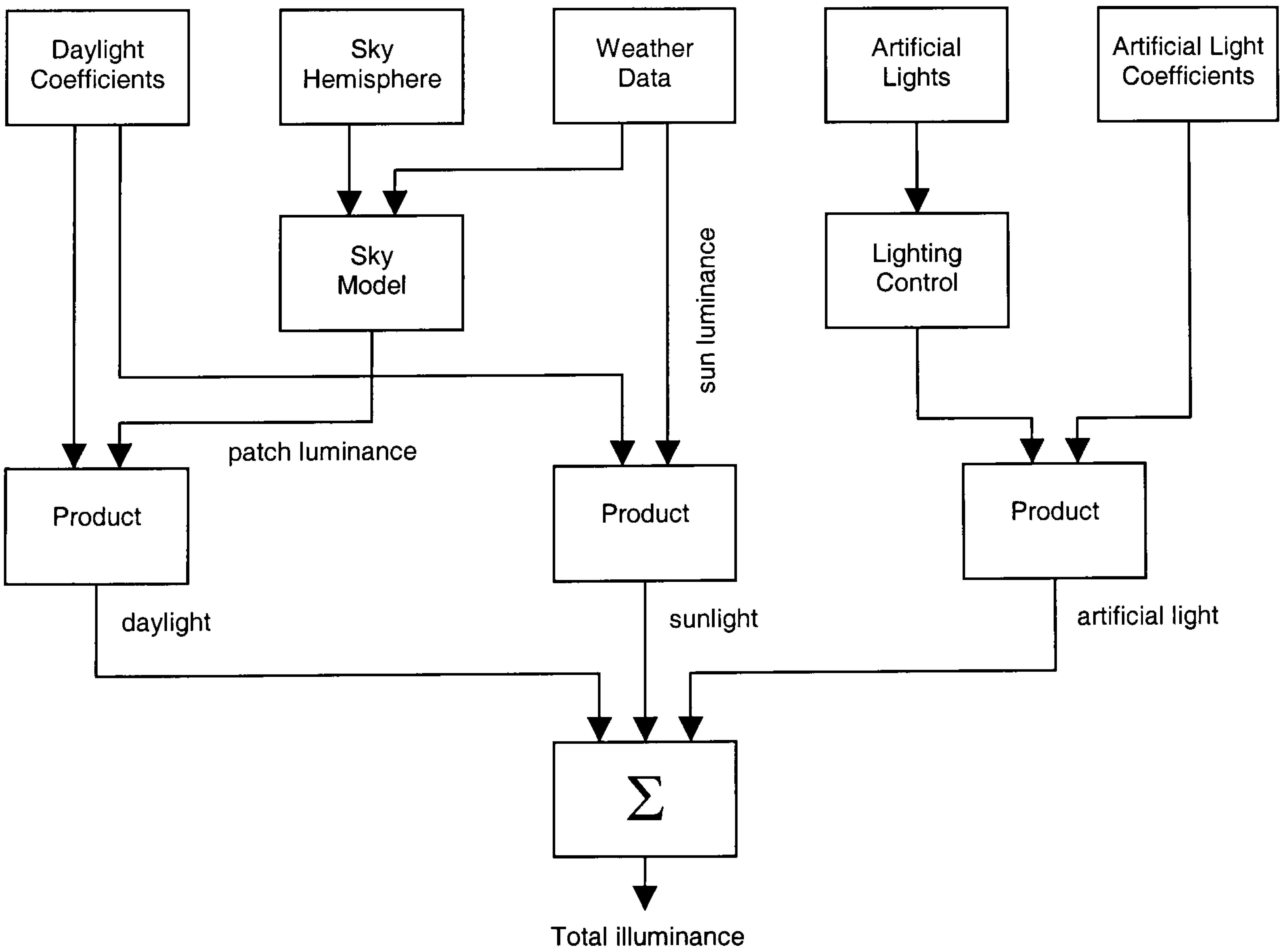

Figure 4.6 Major elements of the DLS used to predict illuminance

The DLS program uses the coefficients to predict illuminance, by assigning realistic luminance values to each light source, scaling those values using the coefficients, and summing the light arriving at each measurement point. This can be repeated varying the time of day, world location, weather conditions, and lighting control system without the need to recalculate the coefficients.

The contribution from daylight is predicted by using the daylight coefficients to scale the luminance of the patches of sky, obtained from weather data and a sky model. The contribution from sunlight is predicted by using the daylight coefficients to scale the luminance of the sun, obtained from weather data. The contribution from artificial light is predicted by using the artificial light coefficients to scale the luminance of artificial lights obtained from a model of the luminaire, controlled by a lighting control system. By recording the lengths of time luminaires are turned on during the simulated period, the electrical power consumption can also be calculated.

The methods used to predict illuminance are described in more detail in chapter 6 .

4.8 Summary

The DLS is designed to run on any computer platform for which a version of RADIANCE is available. The DLS is written using the programming language Java, to provide a common GUI on all platforms.

The DLS reads standard RADIANCE geometry files, and displays a wire-frame representation of the building. The user is able to select building surfaces on which to place luminaires and measurement points.

Daylight coefficients combined with measured weather data and a sky model are used to predict illuminance due to daylight and sunlight. Artificial light coefficients combined with luminaire models and a model of a lighting control system are used to predict illuminance due to artificial lights. The period of time for which artificial lights are predicted to be on is used to calculate electrical energy consumption.

Chapter

5 Modelling sources of light

5.1 Introduction

This chapter describes how sources of natural light and artificial light are modelled by the DLS. Sources of natural light are modelled by dividing the sky hemisphere into a series of discrete patches and using the size and position of each patch to model a separate light source. By modelling the sky hemisphere in this way, each light source can be assigned a different luminance. This allows different patterns of sky luminance distribution to be represented. Chapter 6 describes how the patches are used to predict both daylight and sunlight. The method of sub-division chosen, results in patches that are all of similar size and shape. Triangular shaped patches are used because they can cover the whole surface of the hemisphere. A vector from the centre of the hemisphere directed towards the centre of each triangle, and the solid angle formed by the triangle, are used to define an equivalent RADIANCE *light* source. A method of forming an initial 40-patch hemisphere is described, followed by how different levels of sky discretisation are achieved by recursive sub-division.

Sources of artificial light are modelled by assigning the light output distribution of luminaires to self-luminous surfaces, which represent the size, shape, and position of the luminaires in the building. The way in which luminaires are modelled is described, followed by the way in which they are stored in a simple database and the characteristics of the luminaires used by the DLS.

5.2 Natural light

When using RADIANCE, distant light sources are defined by a direction vector and the angle at the apex of a cone that has the same solid angle as the source. As the patches of sky are distant lights sources, they are defined in this way.

5.2.1 Defining a sky hemisphere

The sky hemisphere is divided into a series of triangular patches that are of similar size and cover the whole sky area. The triangles are defined by vectors originating at the centre of a hemisphere that pass through the vertices of the triangle, as illustrated in Figure 5.1. When used to define a RADIANCE light source, each triangle is replaced by a vector passing through the centre of the triangle and an apex angle equivalent to the solid angle subtended by the triangle.

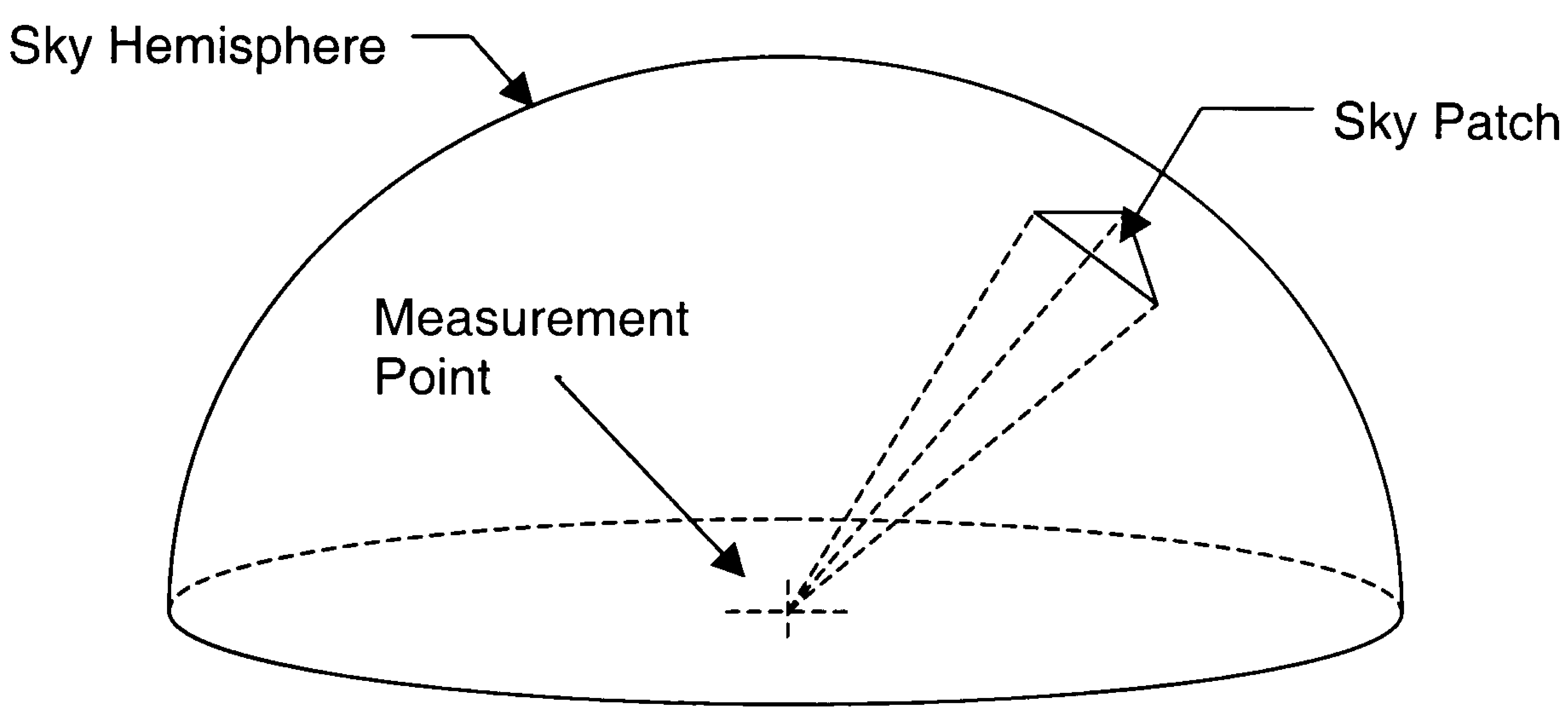

Figure 5.1 A patch on the surface of the sky hemisphere

An initial hemisphere made up of 40 triangles is constructed by dividing faces of an icosahedron, as illustrated in Figure 5.2.

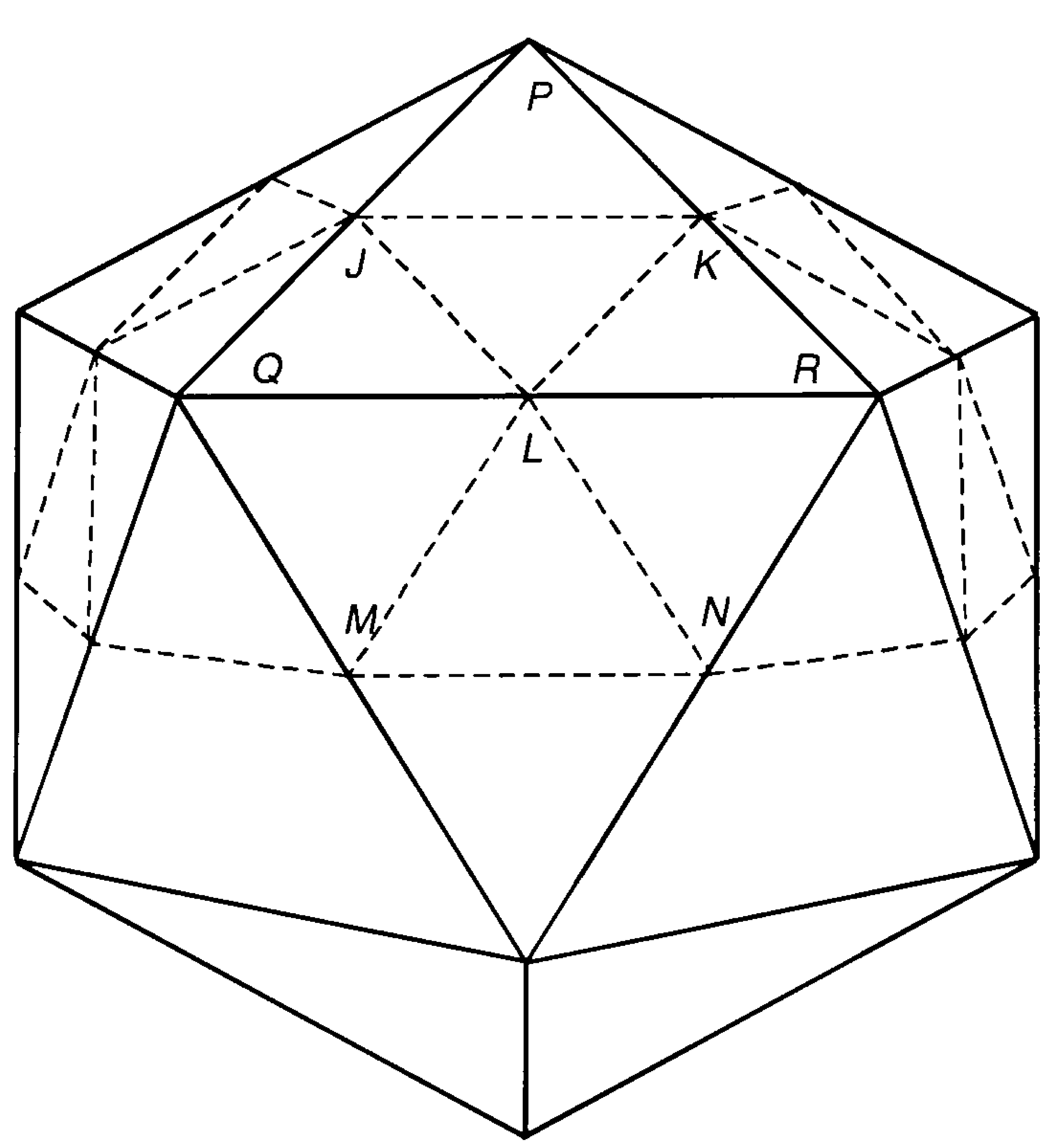

Figure 5.2 Dividing the faces of an icosahedron to form a sky hemisphere

An icosahedron is a regular solid figure with faces that are equilateral triangles. As the vertices of these triangles are equidistant from the centre of the icosahedron, their position is equivalent to those of spherical triangles on the surface of a sphere. The position of these vertices can therefore be defined by a direction vector and the radius of the sphere (or hemisphere). The direction vector is defined by two angles, the zenith angle and the azimuth angle. The zenith angle (θ) is the angle between the vector and the ***z***-axis. The azimuth angle (ϕ) is the angle of rotation of the vector around the ***z***-axis, from the ***x***-axis to the ***y***-axis. Figure 5.3 shows the geometric relationship between the vectors that define the vertices of triangle *PQR* in Figure 5.2.

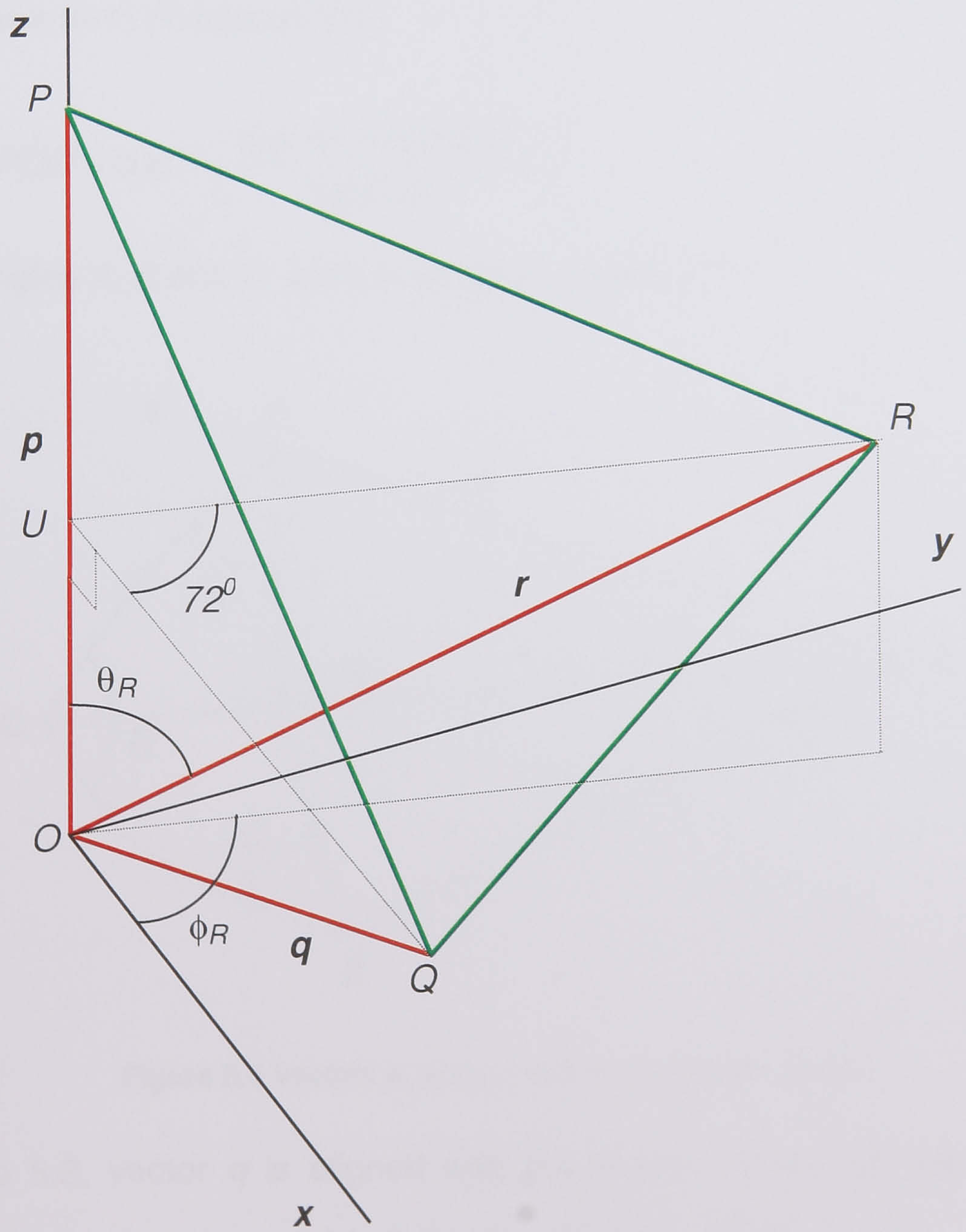

Figure 5.3 The vectors defining face PQR in Figure 5.2

In Figure 5.3, vector ***p*** is aligned along the ***z***-axis. The angle between vectors ***p*** and ***r*** is therefore the zenith angle of vector ***r*** (θ_R). Similarly, the angle between vectors ***p*** and ***q*** is the zenith angle of vector ***q*** (θ_Q) (not shown). If points *P, O* and *Q* are considered to lie in a plane, points *P, O* and *R* in another plane, and points *Q, O* and *R* in a third plane, then the relationship between these planes can be defined in terms of the dihedral angles. A dihedral angle is the angle between two planes, produced by vectors in each plane that are perpendicular to the line of intersection of the planes, e.g. the angle between planes *POQ* and *POR* is angle $Q\hat{U}R$. In an icosahedron, these dihedral angles are all 72^0. If triangle *PQR* is a spherical triangle as illustrated in Figure 5.4, then the angle between vectors ***p*** and ***r*** (θ_R) is given by equation (5-1) [Tregenza 94].

$$P\hat{O}R = \cos^{-1}\left(\frac{\cos A + \cos B \cos C}{\sin B \sin C}\right) \tag{5-1}$$

where angles *A, B* and *C* are the dihedral angles (72^0).

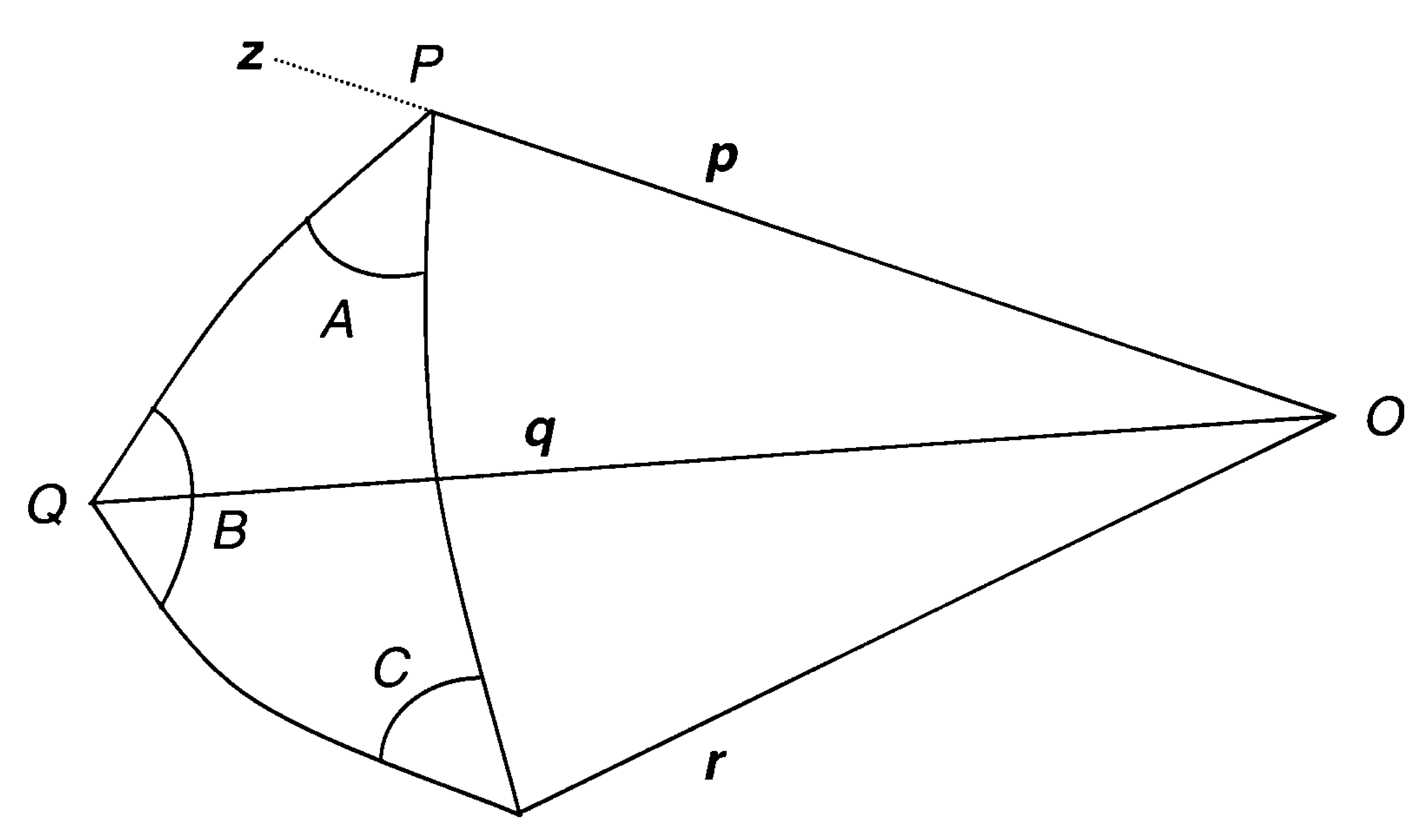

Figure 5.4 Vectors ***p, q*** and ***r*** define a spherical triangle

In Figure 5.3, vector ***q*** is aligned with the ***x***-axis. It can be seen that the azimuth angle of vector ***r*** (θ_R) is the same as angle $Q\hat{U}R$, i.e. 72^0.

Figure 5.5 shows the relationship between vectors ***j***, ***k*** and ***l*** that define triangle *JKL* in Figure 5.2. It can be seen that zenith angle of vector ***k*** (θ_K) is half the zenith angle of vector ***r*** (θ_R). Similarly, the zenith angle of vector ***j*** (θ_J) is half that of vector ***q*** (θ_Q) (not shown).

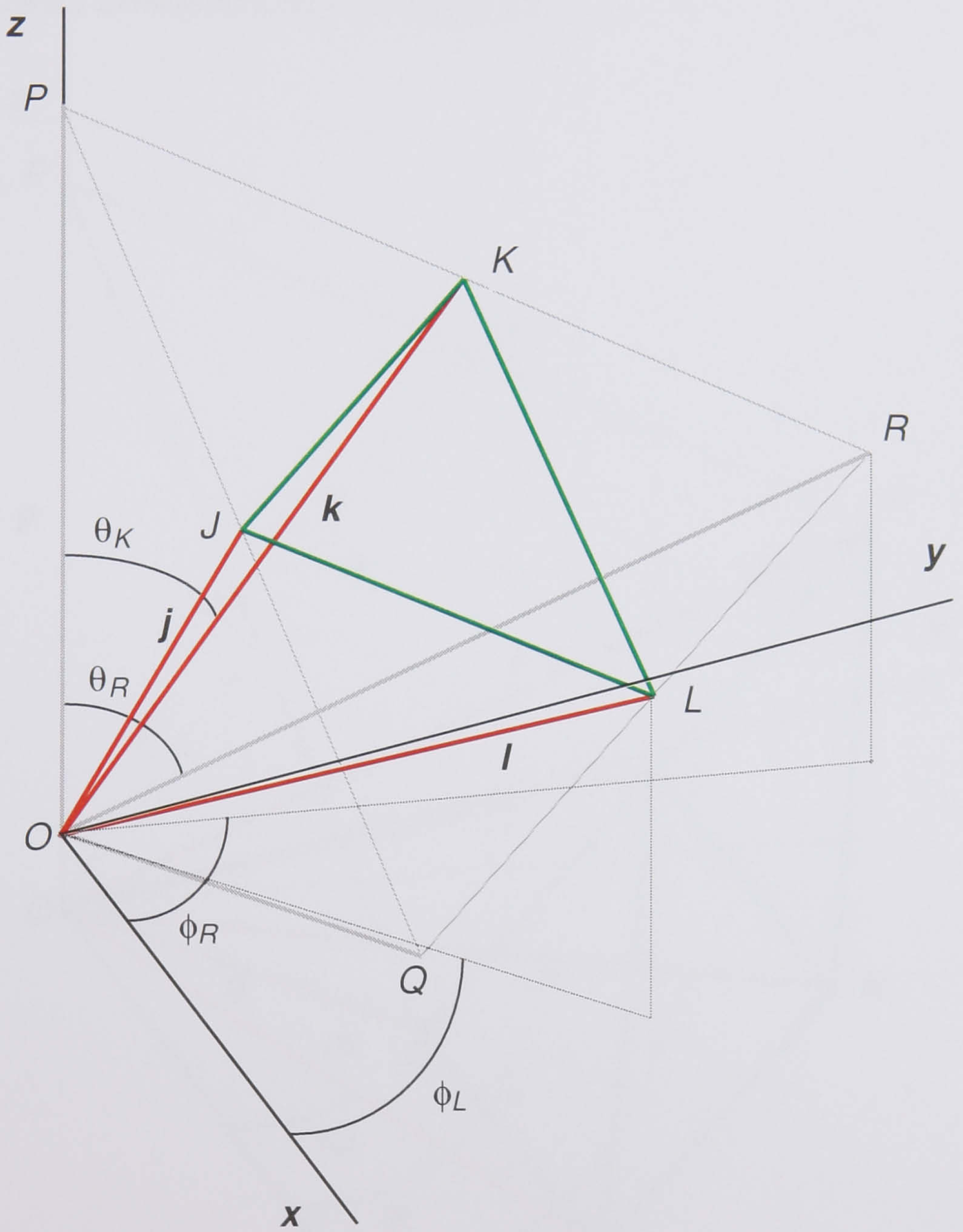

Figure 5.5 The vectors defining triangles *JKL*, *PKJ*, *KRL* and *JLQ* in Figure 5.2

The zenith angle of vector ***l*** is found by averaging the Cartesian coordinates (***x***, ***y*** and ***z***) of vertices *Q* and *R*, and converting the result to polar coordinates.

As vector ***k*** lies in the same plane as vectors ***p*** and ***r***, and vector ***p*** is aligned along the ***z***-axis, the azimuth angle of vector ***k*** (ϕ_K) (not shown) is the same as that of vector ***r*** (ϕ_R). Similarly, the azimuth angle of vector ***j*** (ϕ_J) (not shown) is the same as that of vector ***q*** (ϕ_Q). As vector ***q*** is aligned with the ***x***-axis, the azimuth angle of vector ***l*** (ϕ_L) is half that of vector ***r*** (ϕ_R). It can also be seen in Figure 5.5 that vectors ***p***, ***k*** and ***j*** define triangle *PKJ*, vectors ***k***, ***r*** and ***l*** define triangle *KRL* and vectors ***j***, ***l*** and ***q*** define triangle *JLQ* in Figure 5.2.

Figure 5.6 shows vectors ***m*** and ***n*** that, along with vectors ***q***, ***l*** and ***r***, define triangles *RNL*, *LNM* and *LMQ* in Figure 5.2.

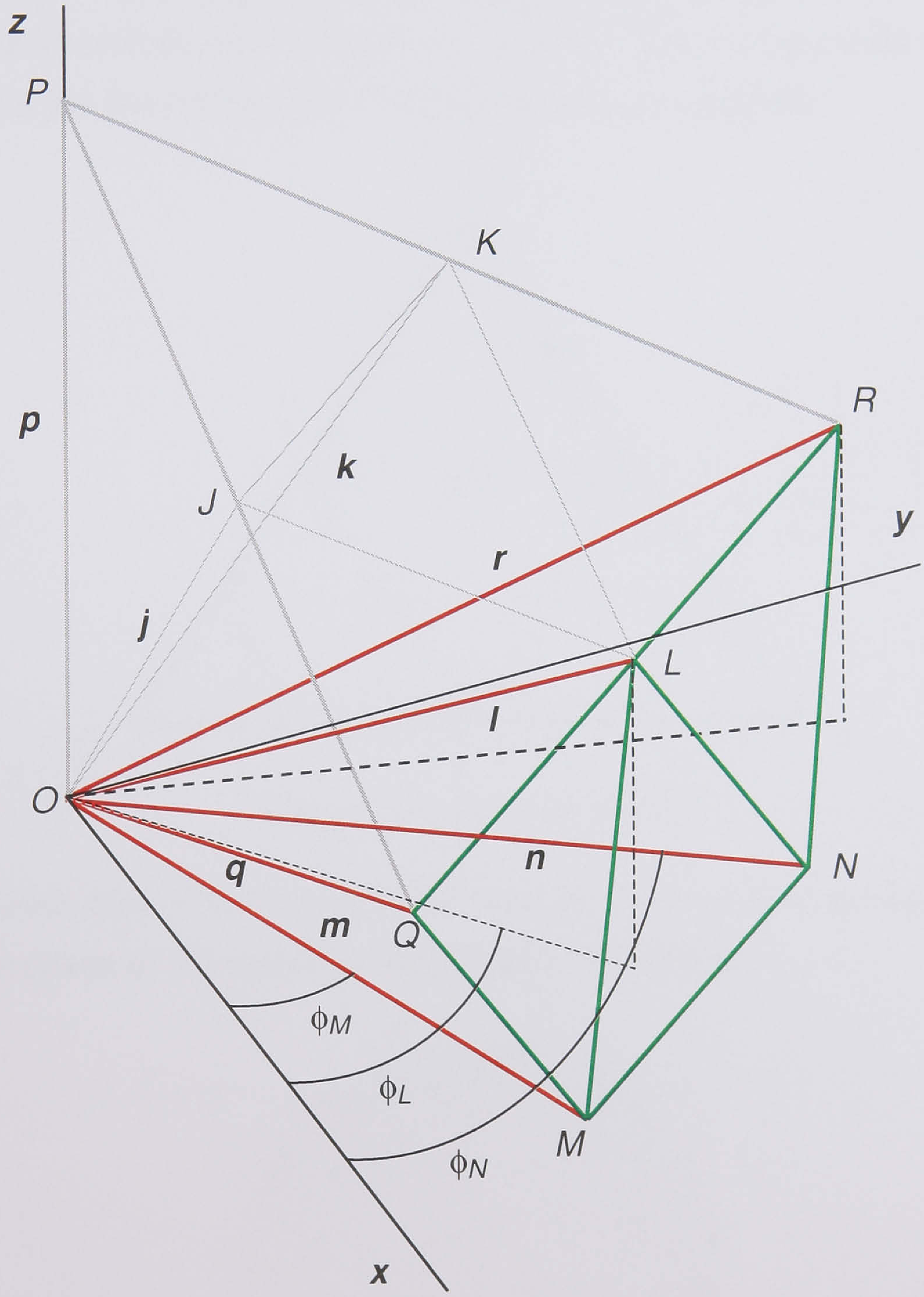

Figure 5.6 The vectors defining triangles *RNL*, *LNM* and *LMQ* in Figure 5.2

It can be seen that vectors ***m*** and ***n*** lie in the ***xy*** plane; the zenith angles of vectors ***m*** (θ_M) and ***n*** (θ_M) (not shown) are therefore 90^0. It can also be seen that the azimuth angle of vector ***m*** (ϕ_M) is half that of vector ***l*** (ϕ_L) and that the azimuth angle of vector ***n*** (ϕ_N) is equal to a combination of ϕ_L and ϕ_N.

The azimuth angles of all other vectors that define the triangles of the 40-triangle hemisphere can found by adding multiples of 72^0 to the azimuth angles of the vectors described.

Different levels of sky discretisation are achieved by recursively sub-dividing the triangles, as illustrated in Figure 5.7. New vectors are derived, mid-way between the vectors defining pairs of vertices of the triangle, by averaging the ***x***, ***y*** and ***z*** co-ordinates of the vectors. Four new triangles are then formed by the vectors (as illustrated) each time this process is repeated.

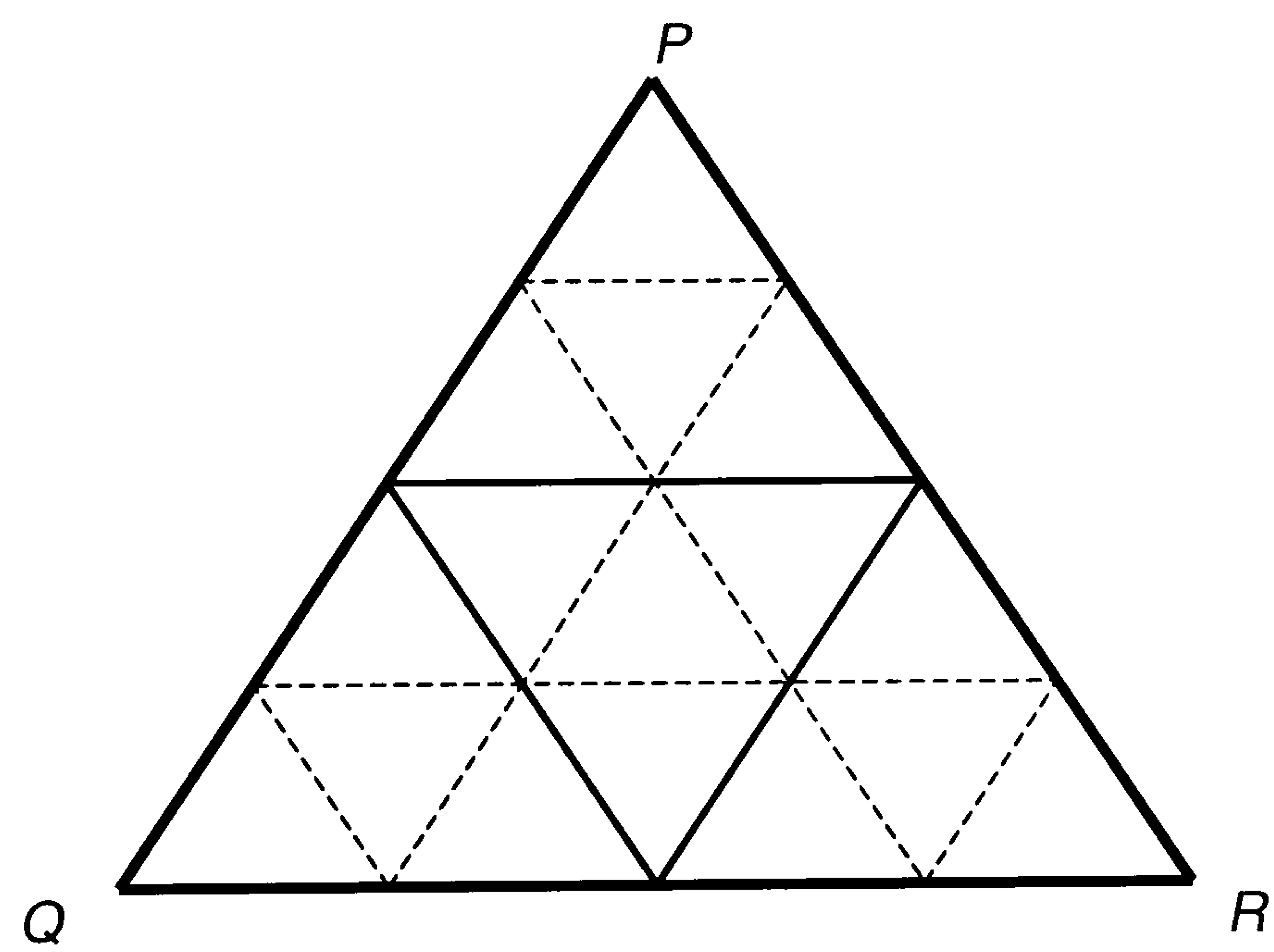

Figure 5.7 Recursive sub-divisions

Dividing each face of a 40-triangle hemisphere into four new faces produces a sky hemisphere of 160 patches, illustrated in Figure 5.8.

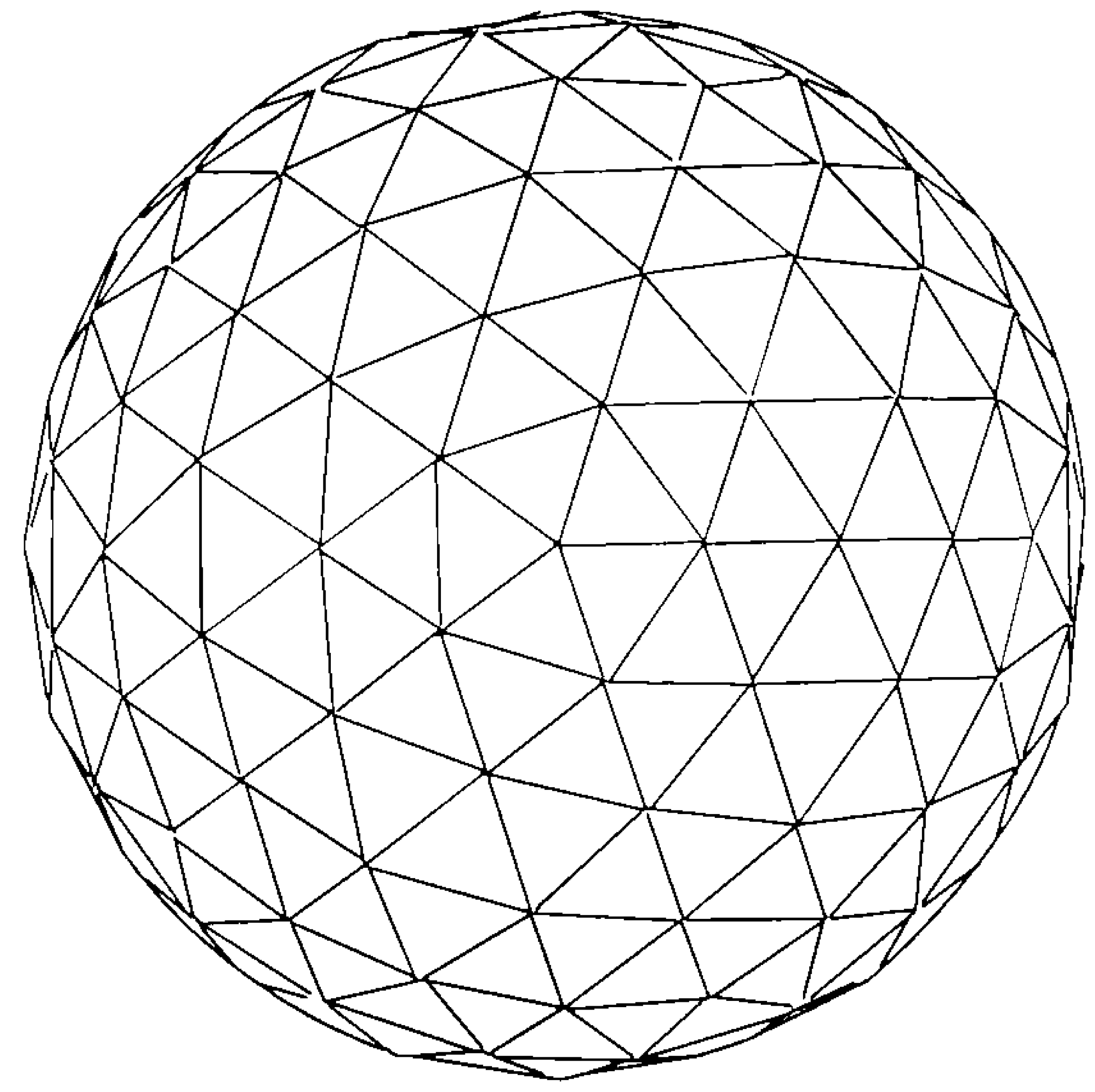

Figure 5.8 Plan view of a 160-triangle hemisphere

Increasing the level of sky discretisation increases the number of daylight coefficients calculated, and hence the time for the system to complete the calculations. However, reducing the size of the individual sky patches improves the accuracy with which the sky luminance distribution can be represented, and, to a limit, increases the accuracy of the predictions.

5.2.2 Description of a sky patch

RADIANCE defines the position and size of a distant *light* source in terms of a direction vector to its centre and the two-dimensional angle at the apex of an equivalent cone.

5.2.2.1 Sky patch position

The location of each sky patch is expressed as a direction vector to the centre of the patch. A vector to the centre of the triangle is found by averaging the ***x***, ***y*** and ***z*** co-ordinates of the three vertices that define the triangle.

5.2.2.2 Sky patch cone angle

The size of a cone can be represented by a three-dimensional solid angle, which is measured in terms of the area on a sphere intercepted by the cone whose apex is at the sphere's centre. One *steradian* (sr) is the solid angle of such a cone that intercepts an area equal to the square of the sphere's radius. The size of a sky patch is therefore the two-dimensional angle ($\hat{A}$) at the apex of a cone that intercepts the same area, and therefore possesses the same solid angle ($\hat{A}_S$) as the spherical triangular sky patch, illustrated in Figure 5.9.

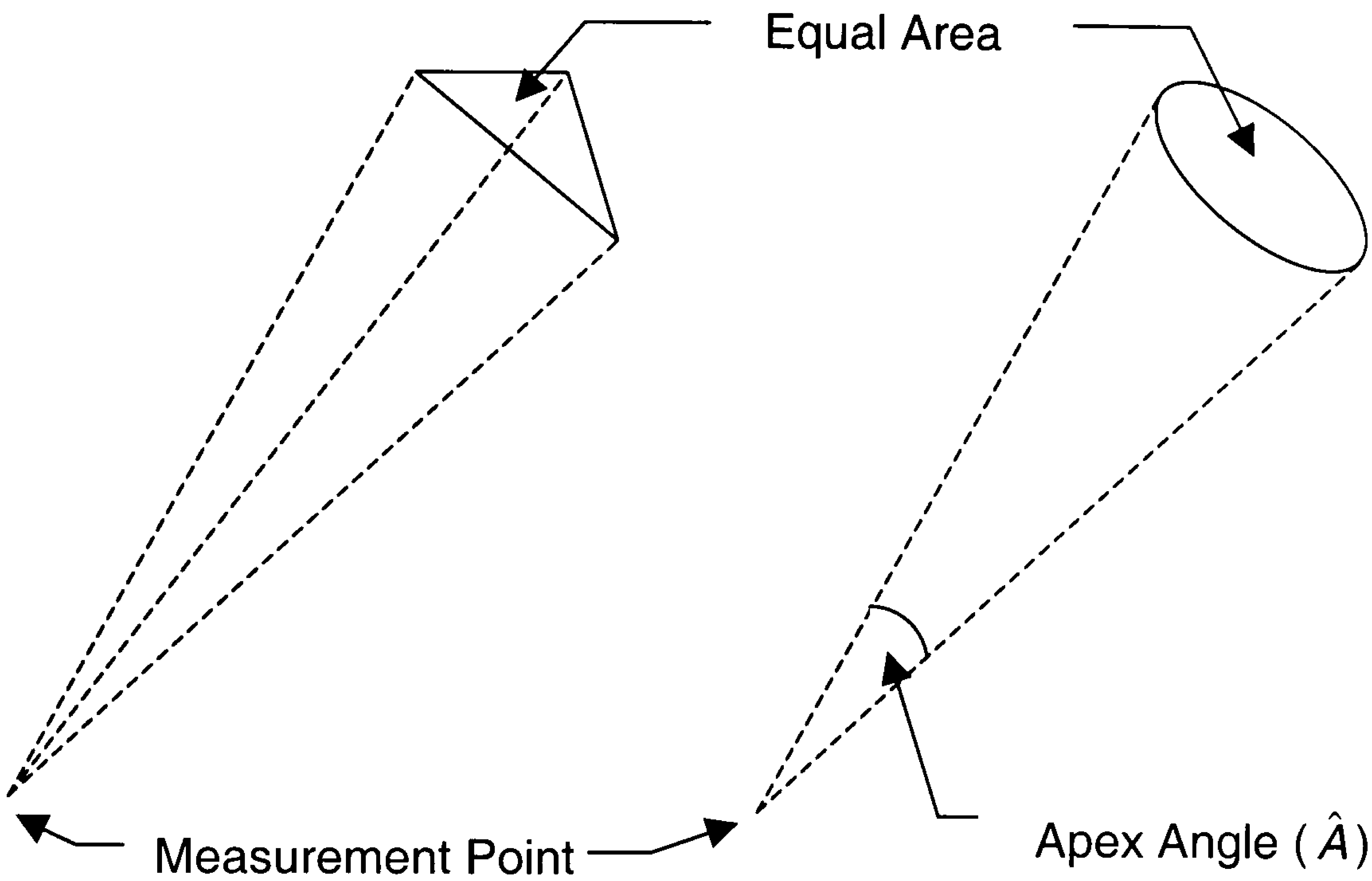

Figure 5.9 Representing a triangular sky patch as a RADIANCE light source

The solid angle of a spherical triangle is given by [Tregenza 94]

$$\hat{A}_S = (A \times B \times C - \pi) \quad sr \tag{5-2}$$

where the dihedral angles *A, B* and *C* are expressed in radians. The relationship between the dihedral angle *A*, in Figure 5.4, and the angles between vectors ***p***, ***q*** and ***r***, is given by [Tregenza 94]

$$A = \cos^{-1}\left(\frac{\cos(Q\hat{O}R) - \cos(P\hat{O}R)\cos(P\hat{O}Q)}{\sin(P\hat{O}R)\sin(P\hat{O}Q)}\right) \tag{5-3}$$

Similar relationships exist for angles *B* and *C*. Using the dot product notation, the angle $Q\hat{O}R$ is given by

$$Q\hat{O}R = \cos^{-1}\left(\frac{q \bullet r}{\|q\|\,\|r\|}\right) \tag{5-4}$$

Similar relationships exist for angles $P\hat{O}R$ and $P\hat{O}Q$.

From the definition of a steradian, the area of a cap (a circular portion of the surface of a sphere) is proportional to the solid angle of a cone with the same diameter as the cap, as illustrated in Figure 5.10. The area (A) of a cap is given by

$$A = 2\pi rt \tag{5-5}$$

where $t =$ the height of the cap and $r =$ the radius.

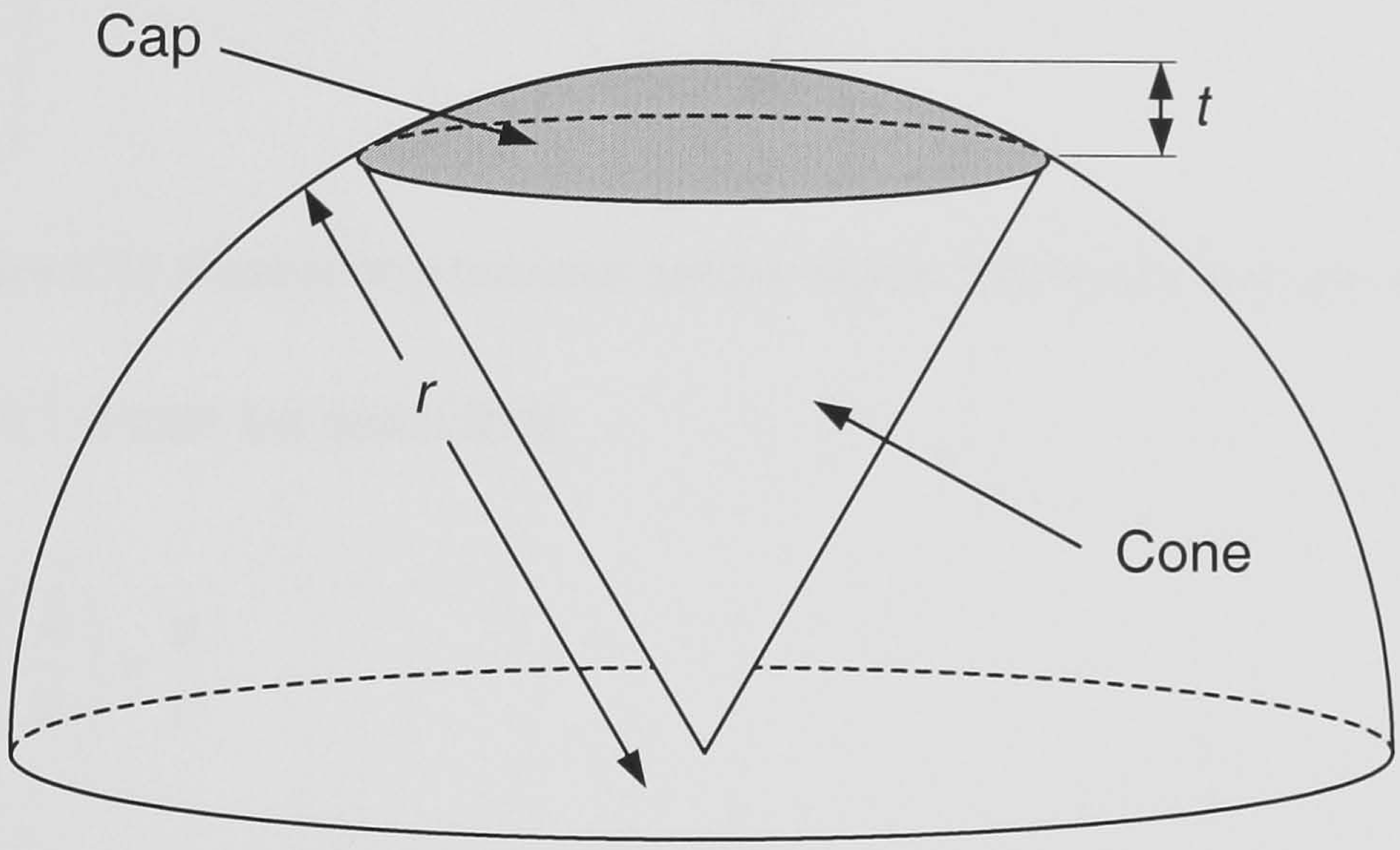

Figure 5.10 A cap defines the area cut by a cone

The area (A) of a cap produced by $\hat{A}_S$ steradians is

$$A = \frac{\hat{A}_S}{4\pi} \times 4\pi r^2 \tag{5-6}$$

(since there are 4π steradians in a sphere and $4\pi r^2$ is the surface area of a sphere).

Equating (5-5) and (5-6) gives

$$2\pi rt = \hat{A}_S r^2 \tag{5-7}$$

$$\therefore t = \frac{\hat{A}_S r}{2\pi} \tag{5-8}$$

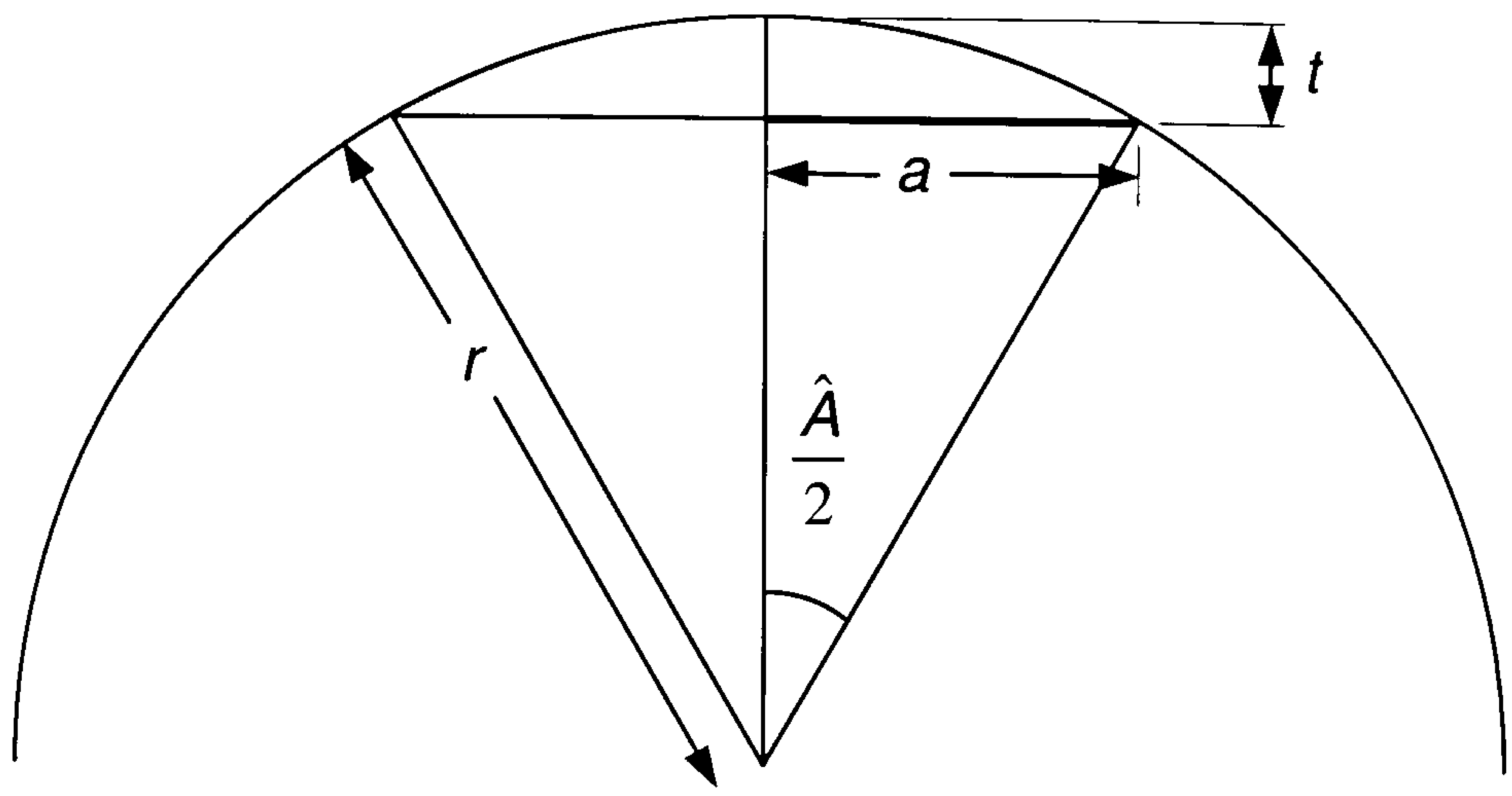

Figure 5.11 Relationship between sphere radius, cap height and cap radius

In Figure 5.11 it can be seen that

$$\sin\left(\frac{\hat{A}}{2}\right) = \frac{a}{r} \tag{5-9}$$

$$\therefore a = r\sin\left(\frac{\hat{A}}{2}\right) \tag{5-10}$$

From the geometric theorem of intersecting chords

$$a^2 = t(2r - t) \tag{5-11}$$

Substituting (5-8) and (5-10) into (5-11), and considering the unit sphere ($r = 1$) gives

$$\sin^2\left(\frac{\hat{A}}{2}\right) = \frac{\hat{A}_S}{2\pi}\left(2 - \frac{\hat{A}_S}{2\pi}\right) \tag{5-12}$$

Solving this equation, as follows, gives an equation for converting a solid angle ($\hat{A}_S$) to a cone angle ($\hat{A}$).

Subtracting 1 from both sides and rearranging gives

$$1-\sin^2\left(\frac{\hat{A}}{2}\right)=1-\frac{\hat{A}_S}{2\pi}\left(2-\frac{\hat{A}_S}{2\pi}\right) \quad \textbf{(5-13)}$$

Using trigonometric identity [Fernando 67] $\cos^2\theta+\sin^2\theta=1$, which can be rearranged to give $\cos^2\theta=1-\sin^2\theta$, and factorising the RHS gives

$$\cos^2\left(\frac{\hat{A}}{2}\right)=\left(\frac{\hat{A}_S}{2\pi}-1\right)^2 \quad \textbf{(5-14)}$$

Thus,

$$\cos\left(\frac{\hat{A}}{2}\right)=\pm\left(\frac{\hat{A}_S}{2\pi}-1\right) \quad \textbf{(5-15)}$$

Since $0<\left(\frac{\hat{A}}{2}\right)<\pi$ radians, $\cos\left(\frac{\hat{A}}{2}\right)$ will always be positive, and since $0<\left(\frac{\hat{A}_S}{2}\right)<2\pi$ steradians, $\left(\frac{\hat{A}_S}{2\pi}-1\right)$ will always be negative.

$$\therefore \cos\left(\frac{\hat{A}}{2}\right)=\left(1-\frac{\hat{A}_S}{2\pi}\right) \quad \textbf{(5-16)}$$

$$\therefore \hat{A}=2\cos^{-1}\left(1-\frac{\hat{A}_S}{2\pi}\right) \quad \textbf{(5-17)}$$

This can be simplified as follows.

Using trigonometric identities $\cos 2\theta=\cos^2\theta-\sin^2\theta$ and $\cos^2\theta=1-\sin^2\theta$ gives $\cos 2\theta=1-2\sin^2\theta$, and therefore $\cos\theta=1-2\sin^2\frac{\theta}{2}$. Substituting in equation (5-16) gives

$$1-2\sin^2\left(\frac{\hat{A}}{4}\right)=\left(1-\frac{\hat{A}_S}{2\pi}\right) \tag{5-18}$$

$$\therefore \sin^2\left(\frac{\hat{A}}{4}\right)=\frac{\hat{A}_S}{4\pi} \tag{5-19}$$

$$\therefore \sin\left(\frac{\hat{A}}{4}\right)=\sqrt{\frac{\hat{A}_S}{4\pi}} \tag{5-20}$$

$$\therefore \hat{A}=4\sin^{-1}\sqrt{\frac{\hat{A}_S}{4\pi}} \tag{5-21}$$

5.3 Artificial light

5.3.1 Modelling artificial lights with RADIANCE

Artificial lights can be modelled using basic RADIANCE geometric shapes and specifying the surface(s) as being self-luminous (*light* type). Modern luminaires however, can have complex patterns of light output distribution, resulting from multiple internal reflective surfaces. In theory, the internal geometry of such luminaires could be modelled using RADIANCE to trace the paths of internal reflections. In practice, the time taken to perform such calculations can be prohibitive. RADIANCE therefore provides an alternative solution. A luminaire can be modelled using one or more simple polygons and a pattern of light output distribution associated with each polygon. A collection of luminaire descriptions, that define the physical shape and light output distribution, is available from the RADIANCE Internet site, described using a format defined by the Illuminating Engineering Society (IES) of North America.

IES format files are used by the DLS to describe luminaires. Commonly used luminaires are stored by the DLS in a simple database.

5.3.2 The DLS luminaire database

Each luminaire description that is held in the database contains the following: a reference to the IES data file, information obtained from the IES file, and information supplied by the user. The IES file format comprises two parts; a descriptive part that includes information such as the manufacturers part number etc., and a technical part that defines the optical and electrical characteristics of the luminaire. The descriptive part does not always conform to a strict format. The IES file specification defines conventions that may, or may not, be adhered to. When a new IES format file is added to the luminaire database therefore, the DLS attempts to identify the various elements and place them in the appropriate fields of the database. The full descriptive part is also supplied to the user so that any information that could not be identified can be entered into the appropriate fields by the user.

Descriptive Part

```
IESNA:LM-63-1995
[TEST]    2101115
[MANUFAC]  Ledalite Architectural Products  604-888-6811
[LUMCAT]   8711T10PE
[DATE]     07/Jan/2000
[_FIXTURE]  Extruded aluminum housing
[_OPTIC]
[LAMP]     F32T8
[BALLAST]   ELECTRONIC
[LUMINAIRE] RLS
[_ALIGN]   SYMMETRIC--0 degree plane parallel to lamps
[_WATT]    30.0
TILT=NONE
```

Technical Part

```
1 2900.0 1.00 37 5 1 1 0.41 4.00 0.00
1.00 1 30.0
0.0 2.5 5.0 7.5 10.0 12.5 15.0 17.5 20.0 22.5 25.0 27.5 30.0 32.5 35.0 37.5
40.0 42.5 45.0 47.5 50.0 52.5 55.0 57.5 60.0 62.5 65.0
 67.5 70.0 72.5 75.0 77.5 80.0 82.5 85.0 87.5 90.0
0.0 22.5 45.0 67.5 90.0
654.3 653.8 652.6 649.8 644.6 636.2 625.7 613.6 600.0 586.1 569.9 551.8
532.6 511.2 488.9 464.5 435.8 400.3 359.0 305.7 245.0
 180.5 118.0 66.6 32.1 16.0 9.6 6.4 4.2 2.8 1.8 1.3 0.7 0.2 0.0 0.0 0.0
654.3 654.4 654.5 653.5 650.5 646.4 640.5 632.6 625.0 616.7 607.2 596.5
584.6 570.8 555.6 538.7 516.7 482.6 436.4 379.8 309.0
 234.8 161.0 93.6 49.2 22.7 12.0 7.5 4.9 3.3 2.3 1.4 0.8 0.4 0.1 0.0 0.0
654.3 655.1 658.6 662.9 667.5 671.6 675.3 678.4 680.8 683.4 685.5 686.7
686.1 682.2 674.3 659.9 635.1 598.2 549.6 493.1 424.5
 352.4 277.7 202.2 132.3 79.4 42.4 20.3 9.3 4.9 3.0 2.0 1.5 1.1 0.7 0.3 0.0
654.3 657.7 664.6 673.3 683.6 694.5 706.7 719.0 732.5 745.9 756.9 764.5
767.6 761.3 743.5 713.2 671.1 619.1 560.7 487.9 410.0
 330.7 254.4 190.2 135.7 91.6 64.0 43.2 23.2 8.9 3.1 1.8 1.3 0.9 0.7 0.2 0.0
654.3 656.7 663.7 673.7 685.2 697.9 712.7 729.5 748.0 766.1 782.1 795.4
802.6 797.8 778.1 746.0 701.9 653.1 592.8 519.4 439.6
 363.1 286.0 213.5 146.4 109.8 85.7 64.6 45.0 22.5 8.1 2.4 1.6 1.2 1.1 0.9 0.1
```

Figure 5.12 Example IES format luminaire description

The DLS attempts to identify the following descriptive items:

- the name of the manufacturer
- a description of the luminaire
- a catalogue reference for the luminaire
- a description of the lamp
- a catalogue reference for the lamp

The technical part of the file must adhere to a strict format. The DLS extracts the following numeric values from the file and places them in the appropriate database fields:

- the number of lamps
- the luminous output of each lamp
- the power consumption

In addition to the information obtained from the IES file, the following information can also be added by the user:

- the warm-up time - the time taken (in seconds) for the luminaire to reach full brightness
- the re-strike time - the time (in seconds) after a luminaire is switched off before it can be switched back on
- the burn time - the expected life (in hours) of the lamp(s)
- the percentage decay - the percentage reduction in luminous output of the lamp(s) during their expected life
- a BZ value - a numeric value in the range 1 to 10 that indicates the approximate pattern of illuminance distribution; a value of 1 corresponds to a highly directional source, a value of 10 to a diffuse source
- whether the luminaire can be dimmed

If the luminaire can be dimmed, an additional power consumption field is enabled, which allows the power consumption obtained from the IES file to be divided into two parts, a constant portion and a variable portion. The constant portion is the power consumed when the luminaire is fully dimmed. The variable portion is the additional power consumed in proportion to the luminaire brightness.

Note: The division of the power consumption into two parts, the warm-up time, the burn time and the re-strike time are not used by the DLS at present. These values have been included to allow for future refinements of the lighting control model.

5.4 Summary

The DLS models sources of natural light by dividing the sky hemisphere into a number of discrete patches. These patches are used to define the size and position of separate light sources. The patches, which are spherical triangles, are defined by vectors originating at the centre of the hemisphere. Equivalent RADIANCE *light* sources are defined by a vector to the centre of the spherical triangle and the angle at the apex of a cone that has the same solid angle.

The DLS models sources of artificial light using luminaires described using the IES file format. The DLS includes a database that enables users to choose from a list of commonly used luminaires when defining a lighting layout.

Chapter

6

Calculating coefficients and predicting illuminance

6.1 Introduction

This chapter describes how lighting coefficients are calculated, and how they are used to predict the level of illumination at measurement points.

The chapter begins by describing how two daylight coefficients are calculated for each patch of sky, a direct daylight coefficient and an indirect daylight coefficient. The method used to calculate artificial light coefficients are then described. The program modules used to calculate daylight and artificial light coefficients are illustrated in Figure 6.1.

The method of predicting natural illuminance due to daylight using daylight coefficients is described, including how the luminance distribution across the sky hemisphere is determined using locally gathered weather data, a sky model and a luminous efficacy model. The method of predicting natural illuminance due to sunlight also using daylight coefficients is described. Finally, the method of predicting illuminance due to artificial lights is described, including how artificial illuminance is affected by building occupancy and lighting control systems.

6.2 Daylight coefficients

Daylight coefficients describe the relationship between the luminance of patches of sky and the resulting illuminance at measurement points within a building. The DLS calculates two coefficients for each sky patch [Mardaljevic 00]; a direct coefficient, the extent to which the patch directly illuminates the measurement point, and an indirect coefficients, the extent to which reflected light from the patch indirectly illuminates the measurement point.

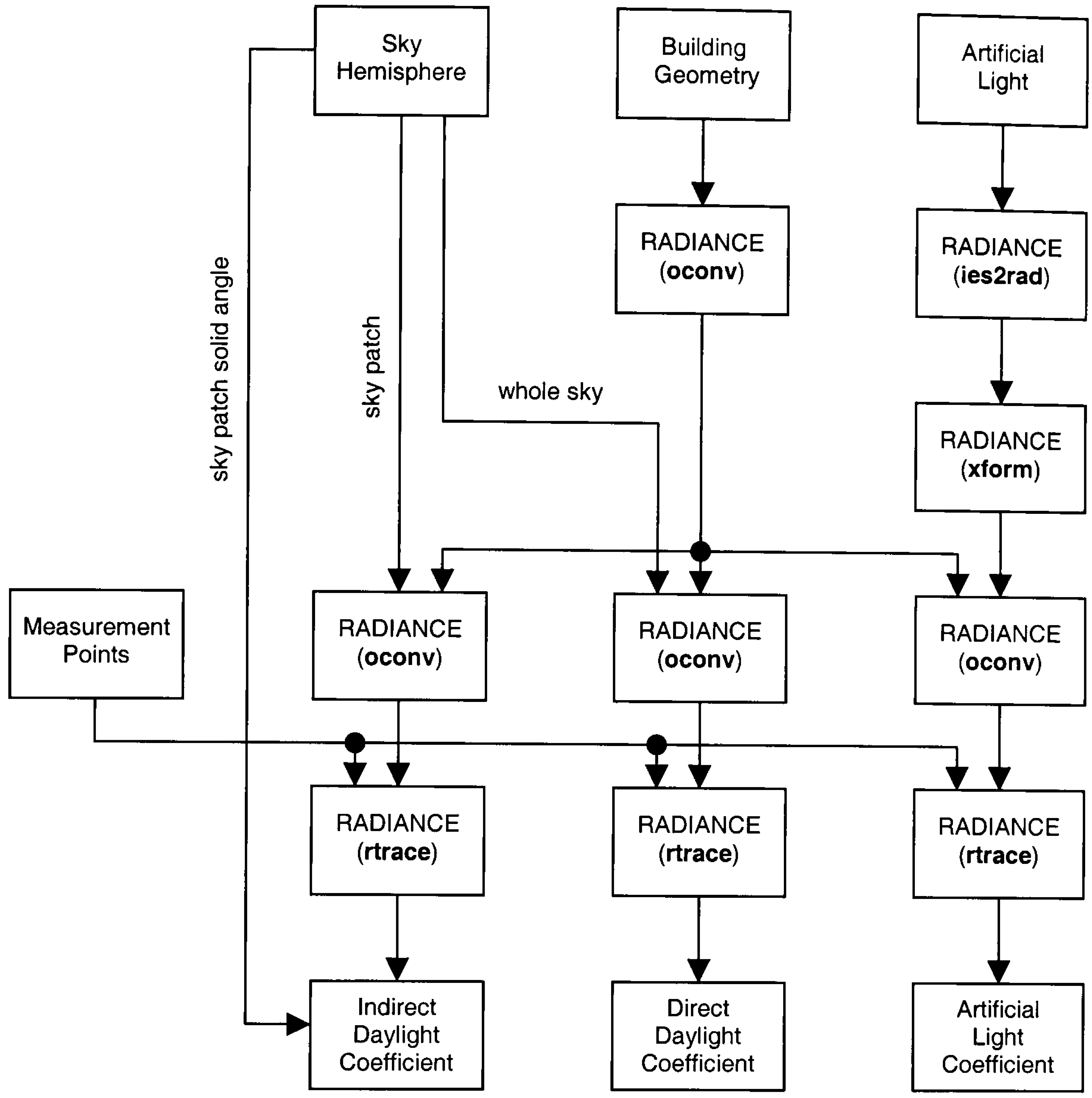

Figure 6.1 DLS and RADIANCE modules used to calculate coefficients (the terms in brackets refer to specific RADIANCE modules)

6.2.1 Direct daylight coefficients

Direct daylight coefficients are calculated by using RADIANCE to determine if specific points on the sky hemisphere are visible from the measurement points, and the attenuation that occurs due to glass or similar materials. The building geometry and the geometry of a complete sky hemisphere that is given unit luminance are converted into a compact data storage structure called an *octree*, using the RADIANCE **oconv** program. The scene is then simulated, using the RADIANCE **rtrace** program to perform direct sampling with the **ab** value (number of reflections) set to zero. Single rays are directed from each measurement point in turn, towards where the patches of a sky hemisphere would be if it were discretised. The number of rays used is equivalent to a level of discretisation of either 160, 640 or 2560 patches, depending on the simulation mode (Low, Medium or High respectively) selected by the user. For each ray, the resulting value will be either zero if the ray hits an obstruction or the sky luminance value (attenuated by any participating media such as glass) if the ray hit the sky hemisphere. This method of calculating the direct component is fast, as it can be carried out by a single RADIANCE simulation. A higher level of sky discretisation can therefore be used to improve sampling accuracy.

6.2.2 Indirect daylight coefficients

Indirect daylight coefficients are calculated in two stages, using each patch of a discretised sky as a single light source. The sky patch geometry, which is given unit luminance, is combined with the building geometry, using the RADIANCE **oconv** program. The scene is first simulated, using the RADIANCE **rtrace** program to perform hemispherical sampling using a high **ab** value. An illuminance value is calculated for the total light, both direct and indirect (reflected), arriving at the measurement point. The simulation is then repeated, with an **ab** value of zero, to calculate the contribution of the direct light only. To isolate the indirect component from the direct component the value obtained without reflections is subtracted from the value obtained including reflections. An indirect daylight coefficient is then obtained by dividing the indirect illuminance by the solid angle of the sky patch. The process is repeated for each combination of sky patch and measurement point. This two-stage process enables the overall indirect daylight contribution to be calculated with adequate accuracy using a relatively coarse sky discretisation.

6.3 Artificial light coefficients

The coefficient approach is also used to predict illumination from artificial lights. The definition of each luminaire is combined in turn with the building geometry and RADIANCE is then used to calculate the amount of light reaching the measuring point. Unlike light from the sky, the distribution of light from a luminaire does not alter, lights are either on or off; and when on, the distribution of output is (to all intent and purpose) the same. It is therefore not necessary to discretise artificial light sources.

The RADIANCE program **ies2rad** is used to translate the IES format data into two RADIANCE format files. The first of these files contains a definition of the simple geometry of surfaces that emit light, centred at the origin. The second file, referenced from the first, contains data used to modify the luminous output distribution of those surfaces to match the distribution of the real luminaire. The RADIANCE **xform** program is then used to rotate and translate the luminaire geometry to the desired location within the building.

To calculate artificial light coefficients, the luminaire geometry is first combined with the building geometry, using the RADIANCE **oconv** program. The RADIANCE **rtrace** program is then used to perform hemispherical sampling, with a high **ab** value. An artificial light coefficient is obtained by dividing the resulting illuminance value by the luminous output of the luminaire, obtained from the IES input file. This normalisation of the coefficient value allows the luminous output to be varied during the prediction phase, because of automatic or manual dimming, or the user specifying a different luminous output.

6.4 Predicting illumination by daylight

The DLS functions used to calculate illuminances due to daylight are illustrated in Figure 6.2. The term daylight refers to all light from the sky hemisphere, excluding light from the sun. The total illuminance due to daylight is the sum of the direct and indirect illuminance from all the sky patches. Each sky patch in turn is assigned a luminance value, obtained from a sky model. The direct illuminance from each patch is the product of the patch luminance, the patch solid angle, and the direct daylight coefficient. The indirect illuminance from each patch is the product of the patch luminance, the patch solid angle, and the indirect daylight coefficient.

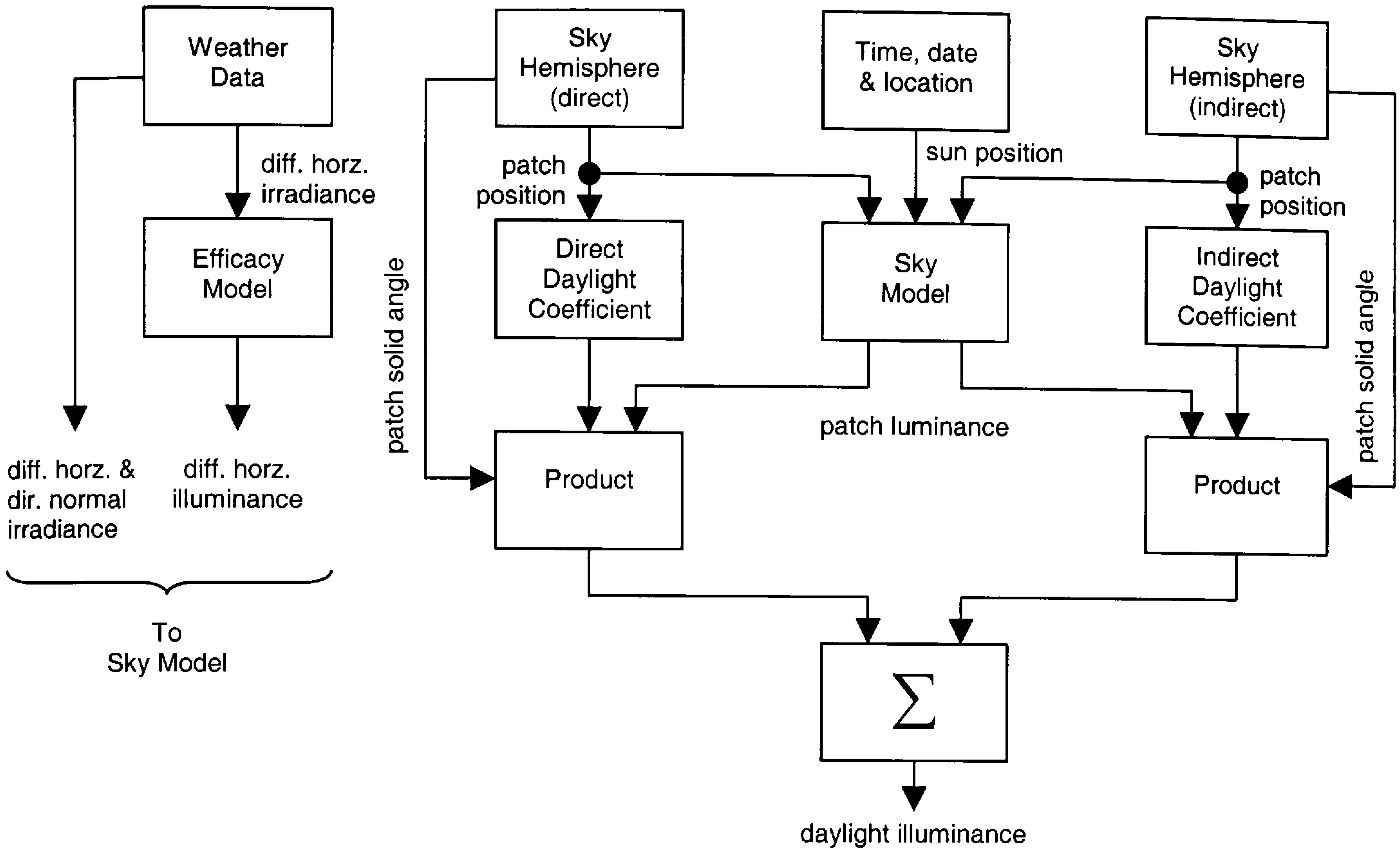

Figure 6.2 DLS functions used to predict illuminance due to daylight

6.4.1 Weather data

In many parts of the world, parameters such as solar irradiation are routinely measured and recorded. The DLS uses locally gathered weather data to determine the sky luminance distributions provided by the sky model, to give a realistic representation of typical climatic conditions that the building under investigation might experience throughout the year. Weather data files typically include hourly averaged values of global horizontal irradiance, diffuse horizontal irradiance and direct normal irradiance. If any one of these values is not included, it can be derived from the other two. Although hourly averaged weather data is commonly collected, the DLS can use data corresponding to any time interval. If the instantaneous time used in each illuminance calculation does not correspond to an entry in the weather data, interpolated values are derived from the two nearest entries.

6.4.2 Luminous Efficacy model

Values of diffuse horizontal irradiance, and direct normal irradiance are converted to illuminance using a luminous efficacy model[1] described in Appendix A.

6.4.3 Sky model

The Perez All-Weather Sky Model [Perez 93], described in Appendix A, is used to define sky luminance angular distribution patterns for a wide range of sky conditions from overcast, through partly cloudy, to clear skies. The actual distribution pattern used at each time step of the simulation is determined by a relationship between the solar zenith angle, the diffuse horizontal irradiance and the direct normal irradiance. The solar zenith angle is calculated from the time of day, day of the year, and the longitude and latitude of the site. The method used to calculate the solar zenith angle is described in Appendix A. Values of diffuse horizontal irradiance and direct normal irradiance are obtained from the weather data.

6.5 Predicting illumination by sunlight

The daylight coefficients are also used to predict illumination due to sunlight. The DLS functions used are illustrated in Figure 6.3. The illuminance at each measurement point is found by scaling direct normal illuminance, using the daylight coefficients corresponding to the sky patch nearest to the sun position, and the solid angle of the sun. Direct normal illuminance is obtained from weather data, converted from direct normal irradiance using the luminous efficacy model (Appendix A).

This strategy effectively shifts the position of the sun slightly. Due to the potentially very high luminance of the sun, and the small angle it subtends, an error in the position of the sun can cause large instantaneous errors in illuminance prediction. This could be avoided by calculating separate

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[1] Private communication - P. Littlefair, BRE

coefficients for sunlight, by placing the sun at the correct position at every time and date required.

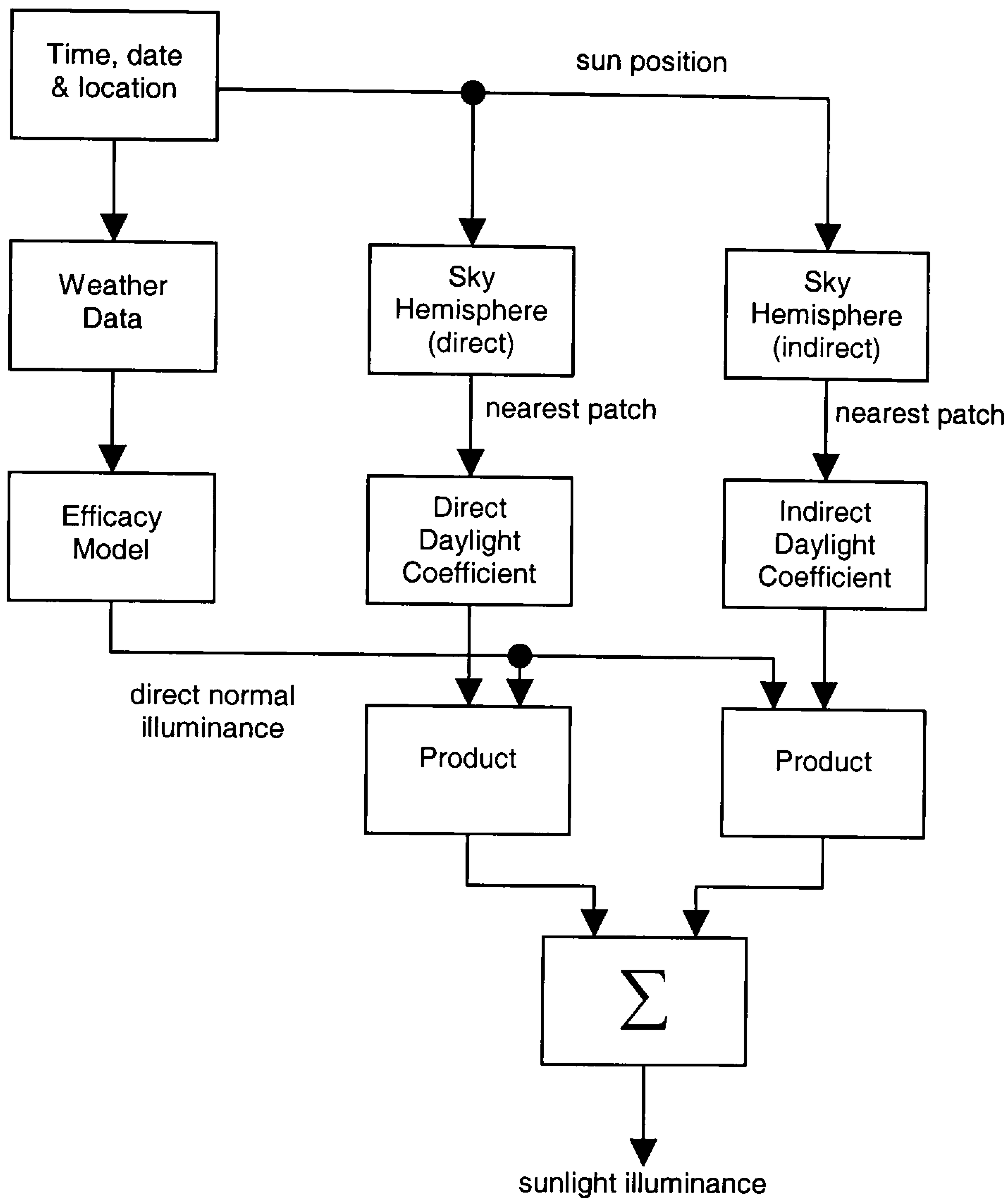

Figure 6.3 DLS functions used to predict illuminance due to sunlight

However, when simulating a whole year with small time-steps this approach would yield a very large number of coefficients. Calculating separate coefficients for sunlight would also result in a fixed relationship between the coefficients, the building geometry, and the world location and orientation of the building.

The overall effect of the error can be reduced in two ways, either by increasing the number of sky patches used to calculate direct daylight coefficients or by using shorter time steps when predicting illuminance. Increasing the number of patches reduces the angle subtended by each patch, reducing the amount by which the angular position of the sun is displaced. When calculating daylight coefficients, the user is able to control the degree of sky discretisation. Using shorter time steps may reduce the period of time during which the error persists, because the illuminance is calculated at the beginning of each time step and is assumed constant until the beginning of the next period. When predicting illuminance, the user is able to select a shorter period than that corresponding to the weather data. As the position of the sun is recalculated at each time step, a new 'nearest sky patch' found, potentially reducing the period during which an error persists.

6.6 Predicting illumination by artificial lights

The DLS functions used to predict illuminances due to artificial lights are illustrated in Figure 6.4. The illuminance at each measurement point due to artificial lights is found by scaling the luminous output of the luminaires using the artificial light coefficients. The total illuminance, both natural and artificial, at a designated measurement point can be used to control light switching. The 'sensor illuminance' provides feedback to a lighting control system, to determine if the luminaires should be on, off or dimmed. As the calculations proceed, the length of time the luminaires are active is recorded, enabling the total energy consumption to be calculated. The frequency of light switching is also recorded.

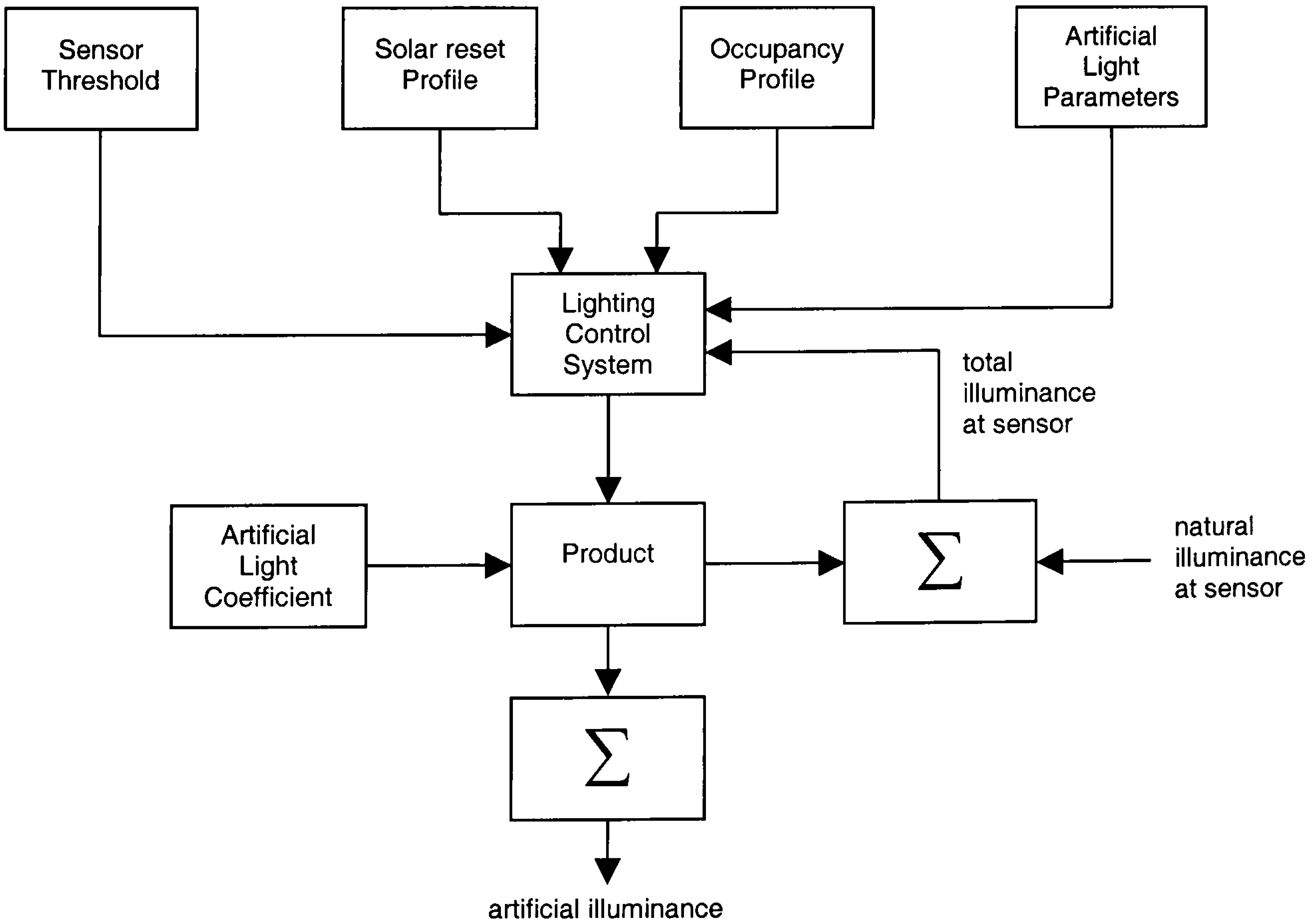

Figure 6.4 DLS functions used to predict illuminance due to artificial lights

6.6.1 Occupancy Profile

In order to predict energy usage for a given lighting control strategy, it is necessary to define when the building is occupied, and hence when artificial illumination might be required. The DLS enables users to define up to four separate occupancy periods during each day of the week. This allows a lunch break period to be specified, also both morning and afternoon breaks if required. The occupancy profile is also used to define the length of the working day, i.e. from the beginning of the first period to the end of the last. It is assumed that lights will be switched off outside the period of the working day. If no profile is defined for a particular day, it is assumed that the building is unoccupied.

6.6.2 Lighting control system models

The function of the lighting control system is to determine if the lights should be on or off. The DLS provides two types of lighting control system model, manual switching and photoelectric switching.

6.6.2.1 Manual switching model

The manual switching model is based on the probability (*p*) that a person entering a room will switch the lights on in response to a perceived level of illuminance. Hunt [Hunt 80] derived the following formula for calculating this probability, which can be adapted for dynamic modelling. The DLS assumes that the measurement points are placed at the working plane height and that the lowest value of illuminance due to natural light at those points is the minimum working plane illuminance (E_{in}).

If $\log_{10}(E_{in}) \leq 0.843$ then $p = 1$.

If $\log_{10}(E_{in}) \geq 2.818$ then $p = 0$.

Else the value of *p* is given by

$$p = -0.0175 + \left(\frac{1.0361}{1 + e^{(4.0835 \log_{10}(E_{in} - 1.8223))}} \right) \quad \textbf{(6-1)}$$

To simulate the random element of occupant switching, a random number (r) between zero and one is generated. If the probability (p) is greater than r, the lights are switched on. If p is less than r, the lights remain off. After each hour of the occupancy period, if the global irradiance is below what it was at the start of the occupancy period, a new probability is calculated and compared with the original random number. If this new probability is greater than r, the lights are switched on. In the DLS model, once the lights are turned on, they remain on until the end of the occupancy period.

Hunt's empirical equation (6-1) was derived without on-site measured illuminance data. The method of determining the minimum working plane illuminance employed by Hunt included the use of a simple orientation factor.

When compared with measured data, this method of calculating minimum working plane illuminance has been found to underestimate illuminances by around 40%. As this method was used to derive equation (6-1), this underestimation does not cause prediction errors. However, if minimum illuminance value is calculated using a more accurate method then the value must be reduced by 40% to maintain the internal consistency of the model[1].

The DLS uses the lowest value of illuminance at the measurement points, reduced by 40%, when calculating switching probability.

6.6.2.2 Photoelectric switching model

Whilst the building is occupied, the photoelectric switching model uses the illuminance value at any measurement point, designated by the user as a sensor position, to determine if lights should be on or off. The DLS provides two types of photoelectric switching, single and double threshold switching, which can be selected by the user. When a single threshold is used, the lights are switched on if the illuminance value is less than the threshold value and switched off if the illuminance value is above the threshold value. When two thresholds are used, the lights are switched on if the value is less than the lower threshold value. The lights then remain on until the illuminance value rises above the upper threshold or until the end of the occupancy period.

[1] Private communication - P. Littlefair, BRE.

6.6.3 Solar Reset switching

A problem with on/off photoelectric switching is user reaction, particularly to lights being switched off automatically. One solution to this is to switch the lights off at a time when the space is unoccupied, e.g. during a lunch break, if the level of illuminance has risen above a pre-determined threshold. This is referred to as solar reset switching. The DLS enables users to specify up to four times during each day of the week that solar reset switching can occur. Solar reset switching can be combined with lights being turned on using photoelectric or manual switching.

6.7 Summary

This chapter had described how direct daylight coefficients are calculated by combining a sky hemisphere with the building geometry and establishing what portion of the sky is visible from the measurement points. The two-stage method of calculating indirect daylight coefficients, which combines individual patches of sky with the building geometry and isolates the reflected light arriving at the measurement points, has been described. The method of calculating artificial light coefficients has also been described.

When predicting illuminance using the coefficients, the total illuminance at each measurement point is determined by assigning realistic values of luminous output to each light source, and summing the contribution from all the sources scaled by the corresponding coefficients. The luminance of the sky hemisphere is determined from locally gathered weather data and the pattern of sky luminance distribution determined using a sky model. The luminance of artificial lights is determined from the lamp characteristics and the influence of a lighting control system.

Chapter

7 Comparative testing

7.1 Introduction

The purpose of this chapter is to evaluate the accuracy with which the DLS is able to predict illumination levels and to identify and quantify any discrepancies.

The accuracy of the predictions of natural illuminance is evaluated by comparing predicted values of illuminance with values measured in a test room fitted with plain glazing, and a second test room fitted with two types of light shelf [Aizlewood 93]. The DLS models the sky hemisphere as a series of discrete patches that are used as separate light sources. The relative accuracy of predictions obtained using different levels of sky discretisation is investigated.

The accuracy of the predictions of artificial illuminance is evaluated by comparing predicted values of illuminance with values calculated using photometric data provided by the luminaire manufacturer. The operation of lighting control is tested by comparing light switching, over a typical three-day period, using different light switching algorithms.

7.2 Sources of error

The DLS models the sky hemisphere as a series of discrete patches that are used as separate light sources to enable different patterns of sky luminance distribution to be simulated. Coefficients are calculated that relate the luminance of each patch of sky to the resulting illuminance at each measurement point. The higher the degree of discretisation, the greater is the accuracy with which a sky luminance distribution can be represented. However, the higher the degree of discretisation, the greater the number of coefficients that need to be calculated and the longer it takes to calculate them. For example, it took approximately 6.25 hours to calculate the 2560 indirect daylight coefficients for six measurement points used in the tests described in section 7.4. These calculations were carried out using a 400MHz Pentium II PC, equipped with 128MB of RAM and running the Linux operating system. In addition to the time taken to calculate coefficients, the greater the number of coefficients used, the longer it takes to calculate illuminance predictions using them. Using a lower degree of discretisation enables coefficients, and hence illuminance predictions, to be calculated more quickly, but with reduced accuracy.

There are two ways in which using a lower degree of discretisation results in reduced accuracy when calculating direct illumination. Firstly, when calculating a coefficient for the direct illumination by a patch of sky, the coefficient will be zero unless there is a direct path between the centre of the patch and the measurement point. If the coefficient is not zero, then it will be proportional to the illumination resulting from the whole area of the patch. Cases where only part of the patch is visible from the measurement point can result in too large or too small a contribution by the patch depending upon whether the centre of the patch is visible or not. Two patches that are partially obscured are illustrated in Figure 7.1.

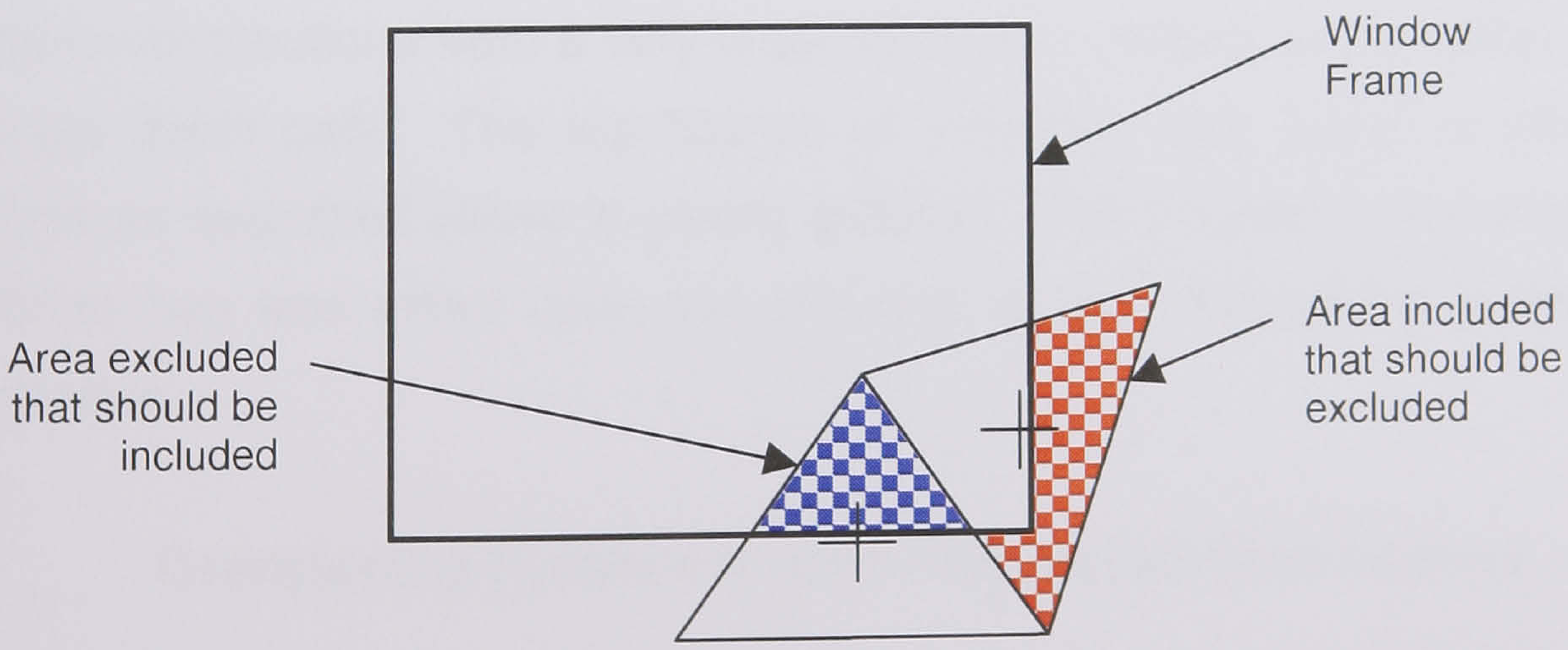

Figure 7.1 Patches that are only partially visible from a measurement point

The area that is shaded blue represents the portion of a patch that is visible from the measurement point, which will not contribute to the illuminance calculation because the centre of the patch is not visible. The area that is shaded red represents the portion of a patch that is not visible from the measurement point, which will contribute to the illuminance calculation

because the centre of the patch is visible. The lower the degree of discretisation, the larger the patches and hence the larger the area of patches that may be included in, or excluded from, the prediction calculations, and therefore the larger the potential errors.

Secondly, when direct illumination by the sun is calculated, the DLS uses the coefficients calculated for the nearest sky patch to scale the luminance of the sun. The lower the degree of discretisation, the greater the maximum difference between the true position of the sun at a given instant and the centre of the nearest patch. This can result in the sun being visible when it should not be, and vice versa. This error may be much more significant because the sun is so bright compared to a single patch of sky. Furthermore, whilst over prediction of illuminance from one patch (red in Figure 7.1) may be compensated for by under prediction from another (blue in Figure 7.1), such compensation cannot occur for the sun, as there is only one. It is possible, however, that some errors resulting from the misplacement of the sun will be compensated for within a sequence of time steps. If the sun is visible at one time step when it should not be, and is not visible at another time step when it should be, the error over the whole time period will be reduced.

When an indirect illumination coefficient is calculated, the resulting value contains contributions from a very large number of indirect paths, rather than a single direct path. The significance of individual rays hitting or missing patches as described above is greatly reduced. The degree of discretisation therefore has less effect upon the accuracy of the calculations of indirect illumination.

7.3 Comparing predicted with measured illuminance

The accuracy of the predictions of natural illuminance is evaluated by comparing values predicted by the DLS with values measured in a test room.

7.3.1 Source of test data

The test data used was gathered under real conditions at the UK Building Research Establishment (BRE). Measurements of internal illuminance were

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7.3.1 Source of test data

The test data used was gathered under real conditions at the UK Building Research Establishment (BRE). Measurements of internal illuminance were

made at six points at working plane height along the centre of a test room fitted with single plain glazing. Measurements were made simultaneously in a second identical adjacent test room, fitted at different times with innovative glazing materials and light redirection devices such as light shelves. Figure 7.2 shows an internal view of one of the test rooms.

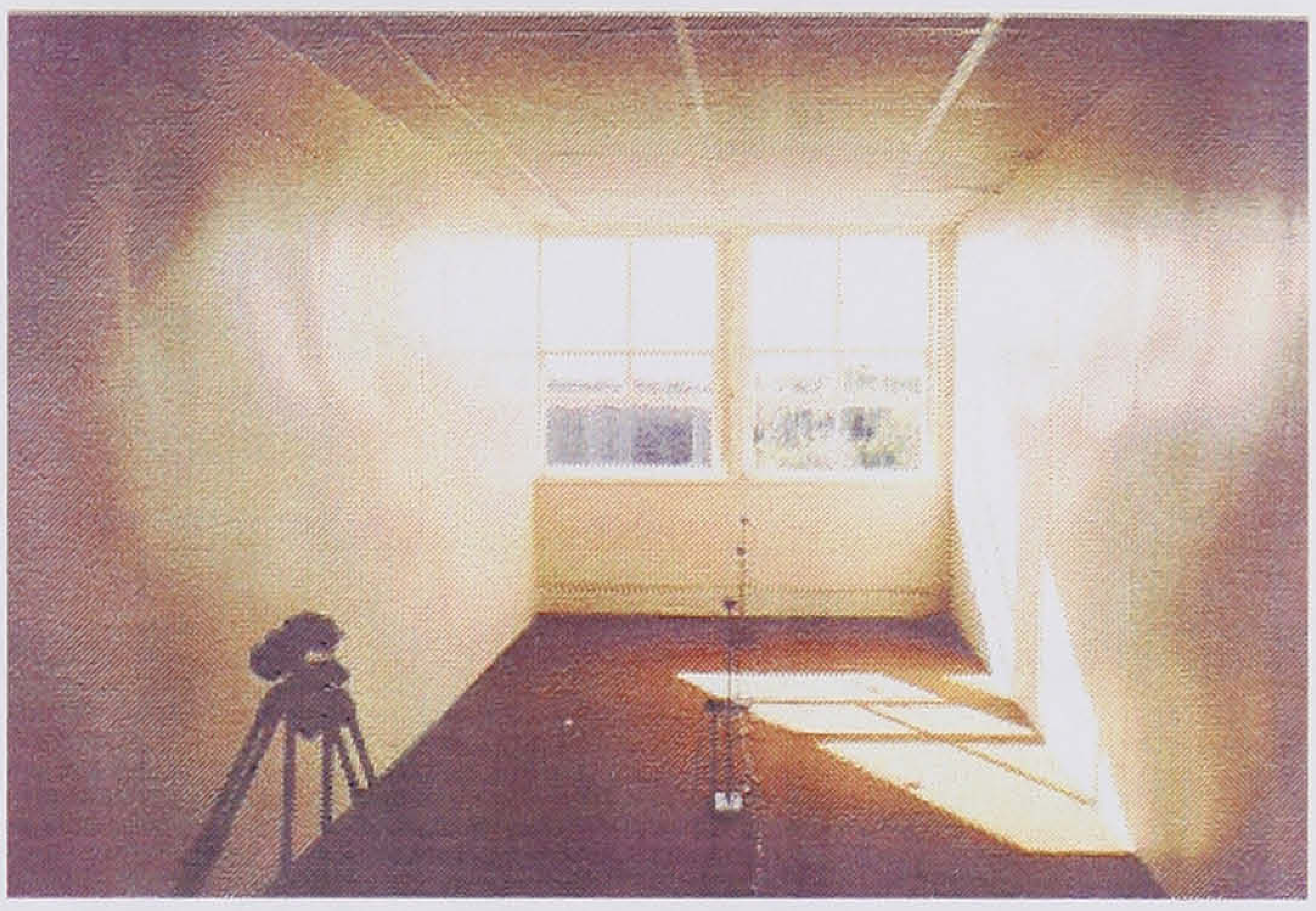

Figure 7.2 An internal view of the BRE test rooms[1]

Figure 7.3 shows the configuration of the test rooms and the relative positions of the photocells. The windows of the test rooms face 16^0 West of South.

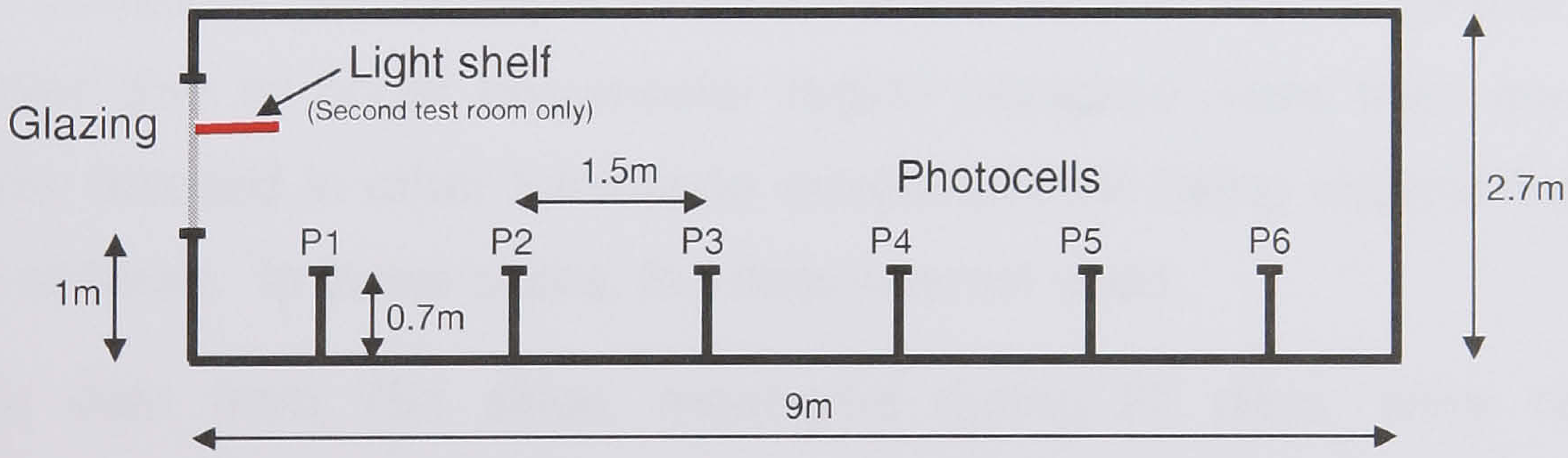

Figure 7.3 Configuration of the BRE test rooms

Global Horizontal Irradiance and Direct Normal Solar Irradiance were measured simultaneously on the roof of the building, immediately above the test rooms. A sky scanner, also located on the roof above the test rooms, with an acceptance angle of 11^0, was used to measure the luminance of 145 patches of sky (illustrated in Figure 7.4) to determine the luminance distribution of the sky hemisphere.

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[1] Picture reproduced courtesy of J Mardaljevic.

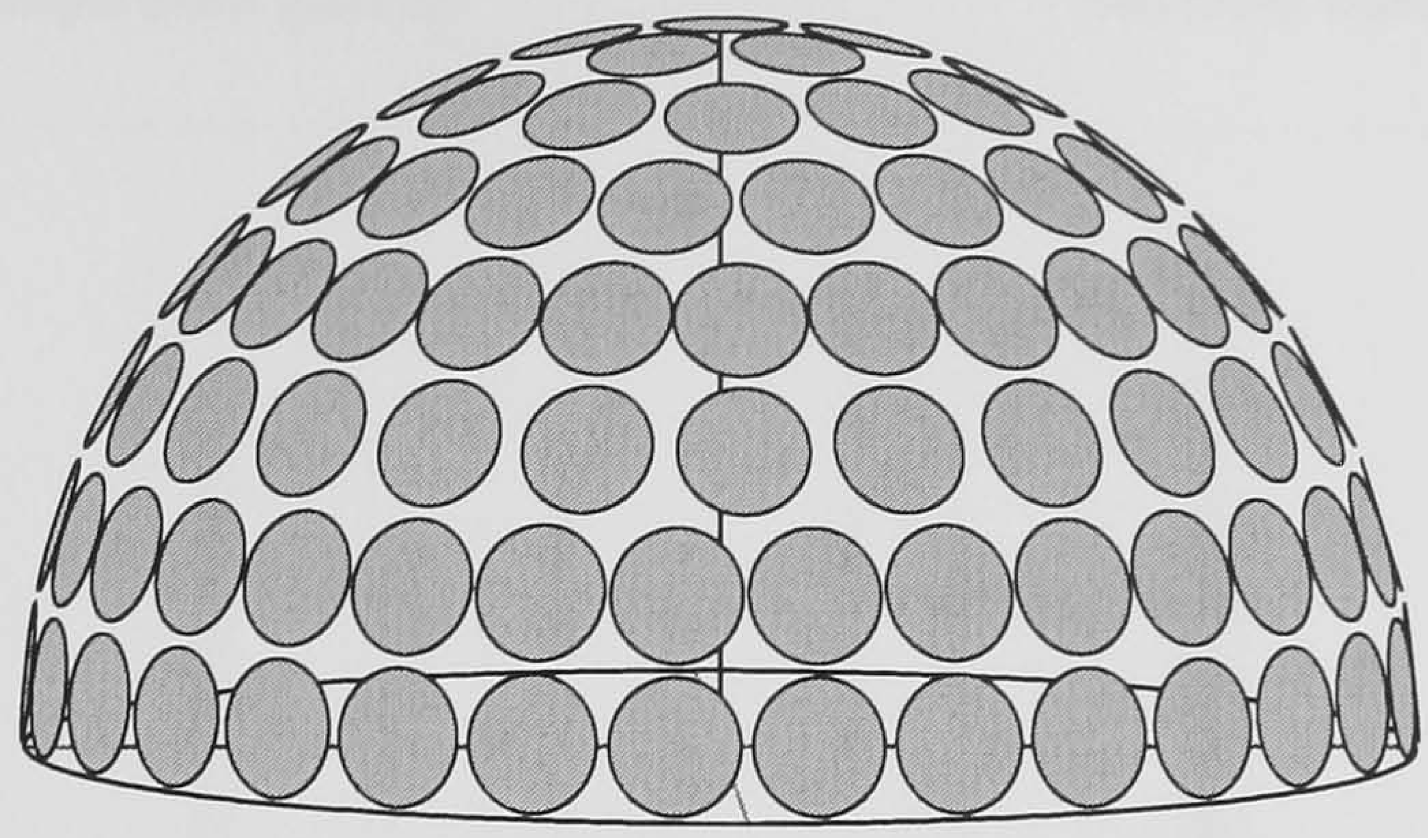


Figure 7.4 Arrangement of the 145 patches of sky sampled by the sky scanner[1]

The sky scanner only provided 144 luminance values, the value for the patch nearest to the sun's position being omitted because the luminance of the sun was too great for the scanner to measure. In order to use the luminance values for testing the DLS, the missing value was obtained by linear interpolation. In Figure 7.4, it can be seen that the sky scanner did not sample the entire sky hemisphere. The patches constitute approximately 68% of the total area [Tregenza 87]. To compensate for this, the luminance values were normalised to the measured value of Diffuse Horizontal Illuminance.

Some conditions, for example when the sun's position was such that part of the solar disc or bright circumsolar region occupied more than one patch position, resulted in other luminance measurements being beyond the range of the scanner. In these cases, the data was not used.

Usable data from 754 skies, measured during 27 days, were obtained covering a wide range of sky conditions, from overcast through intermediate to clear sky conditions [Mardaljevic 00b]. Of these 754 skies, 294 were measured whilst the second test room was fitted with a diffuse reflecting light shelf during late April and May, when the sun was high in the sky, and 65 whilst the room was fitted with a specular reflecting light shelf during November, when the sun was low in the sky. The distribution throughout the days of the year on which the skies were measured is shown in Figure 7.5.

[1] Picture reproduced courtesy of J Mardaljevic.

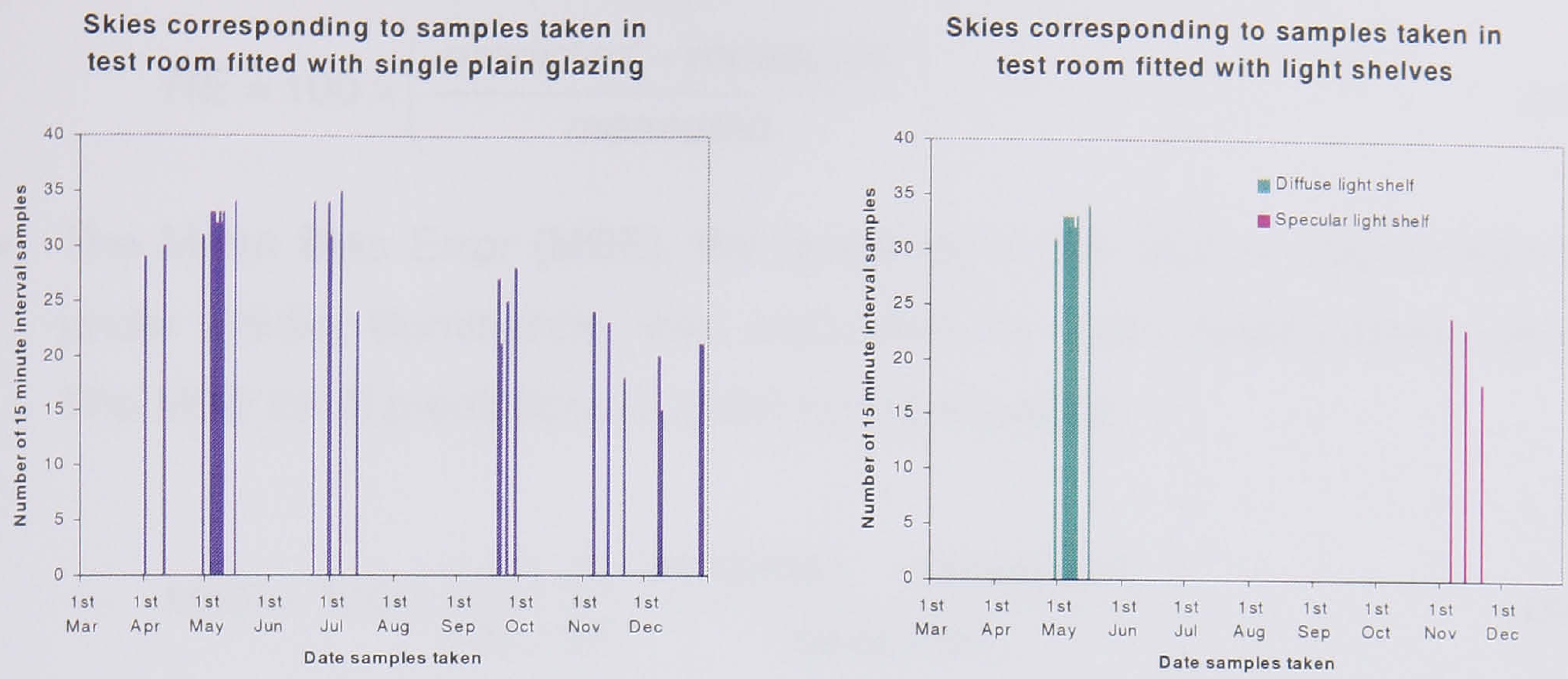


Figure 7.5 Distribution of test data sets measured during 1992

7.3.2 Method of testing

The DLS was used to predict the resulting illuminance at the six measurement points in the two test rooms, and the predicted values compared with the measured values. A high degree of sky discretisation was used to minimise errors relating to patch size and position, 10240 patches were used to provide direct illumination and 640 patches to provide indirect illumination.

In its normal operation, the DLS uses a sky model to provide values of sky luminance when calculating predictions. In these comparisons, the adjusted sky luminance values obtained using the sky scanner were used in place of values normally provided by the sky model to more accurately reflect the conditions under which the internal illuminance values were measured. Each patch of the DLS's discretised sky was assigned the same luminance value as the nearest patch of sky measured by the sky scanner. The Direct Normal Solar Illuminance, obtained from the measured irradiance values, was used to provide the brightness of the sun. The resulting predicted values of illuminance were compared with the values measured in the test rooms in the following ways.

- The Relative Error (RE) between predicted and measured values were calculated for each measurement point and used to show the frequency distribution of the magnitude of the errors. The RE for each prediction is given by the equation: -

$$RE = 100 \times \left(\frac{predicted - measured}{measured} \right) \tag{7-1}$$

- The Mean Bias Error (MBE), the tendency of the DLS to over predict or under predict illuminance, was calculated for each measurement point. The MBE for N predictions is given by the equation: -

$$MBE = 100 \times \left(\frac{1}{N} \right) \sum_{i=1}^{N} \left(\frac{predicted_i - measured_i}{measured_i} \right) \tag{7-2}$$

- The Root Mean Square Error (RMSE), the effective size of the prediction errors, was calculated for each measurement point. The RMSE for N predictions is given by the equation: -

$$RMSE = 100 \times \sqrt{\left(\frac{1}{N} \right) \sum_{i=1}^{N} \left(\frac{predicted_i - measured_i}{measured_i} \right)^2} \tag{7-3}$$

- The Coefficient of Determination (CD), a relative measure of the strength of the linear relationship (correlation) between the pairs of values, was calculated for each measurement point. The resulting value, a number between 0 and 1, can be expressed as a percentage. The CD for N predictions is given by the equation: -

$$CD = \left(\frac{\sum_{i=1}^{N} \left(measured_i - \overline{measured_i} \right) \left(predicted_i - \overline{predicted_i} \right)}{\sqrt{\sum_{i=1}^{N} \left(measured_i - \overline{measured_i} \right)^2 \sum_{i=1}^{N} \left(predicted_i - \overline{predicted_i} \right)^2}} \right)^2 \tag{7-4}$$

where $\overline{measured}$ and $\overline{predicted}$ are the respective arithmetic means.

Section 7.2described potential errors that may result due to the size of discretised sky patches and effective displacement of the sun, when the sun and circumsolar region are visible from the measurement point. In order to identify instances where these errors might occur, the azimuth angles of the sides of the window and elevation angles of the top and bottom of the window were calculated for each measurement point. The instances at which the solar azimuth and elevation angles fell between both pairs of angles were then used to distinguish between cases that might contain such errors and those that do not.

7.3.3 Results obtained from the test room with single plain glazing

Values of illuminance predicted by the DLS for the 754 test cases were compared with values measured in the test room fitted with single plain glazing. Figure 7.6 shows the Relative Error (RE) values plotted on frequency distribution histograms. Values in the range –50% to +50% are grouped into 5% bins, values outside this range into 100% bins.

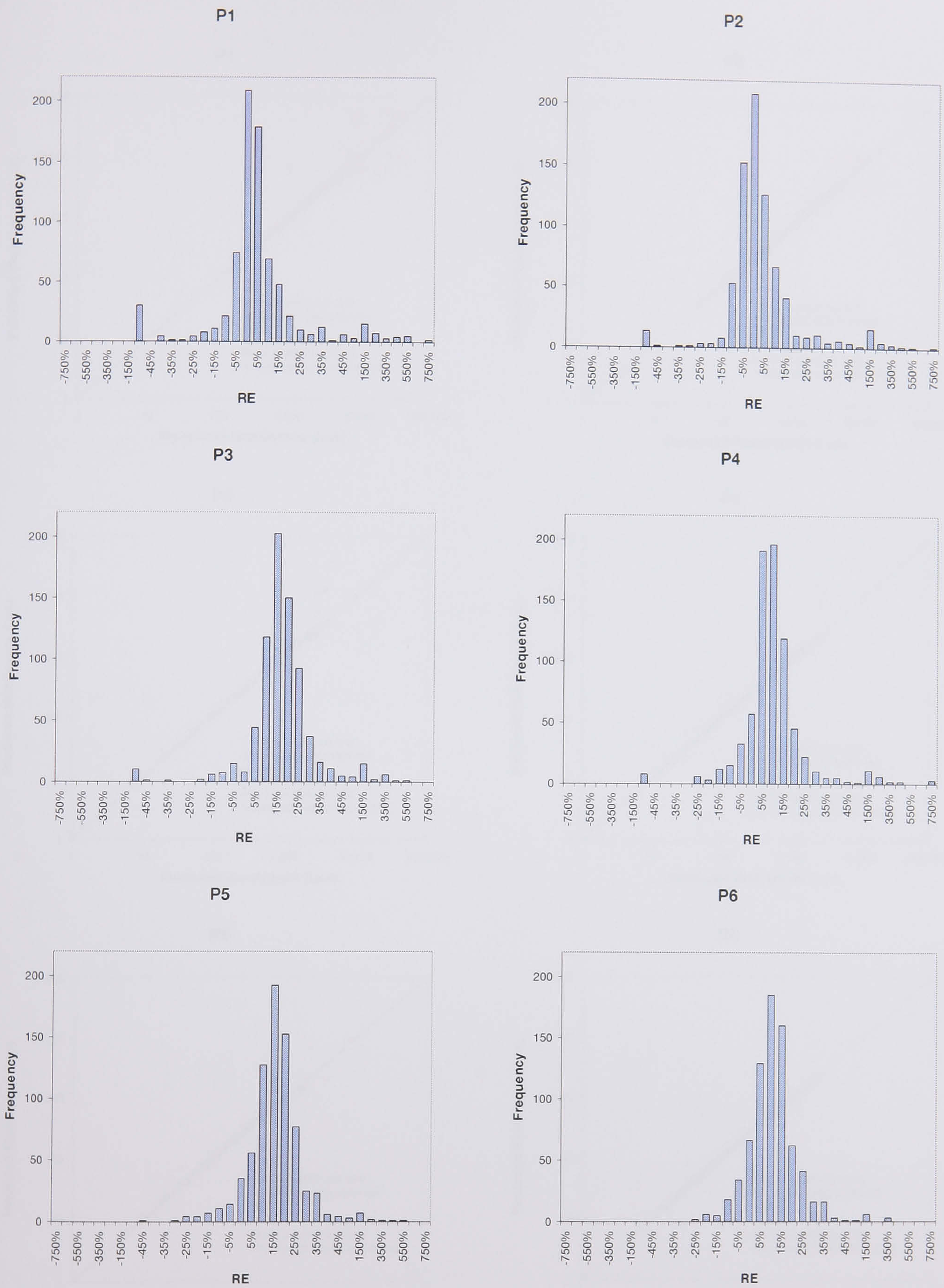


Figure 7.6 Frequency distribution of RE (Relative Error) from test room with single plain glazing, at photo-cells P1 to P6

In Figure 7.7, the predicted values of illuminance are compared with measured values directly. The values coloured red correspond to skies where the sun and circumsolar region is visible at the measurement point, and the values coloured blue correspond to skies where it is not.

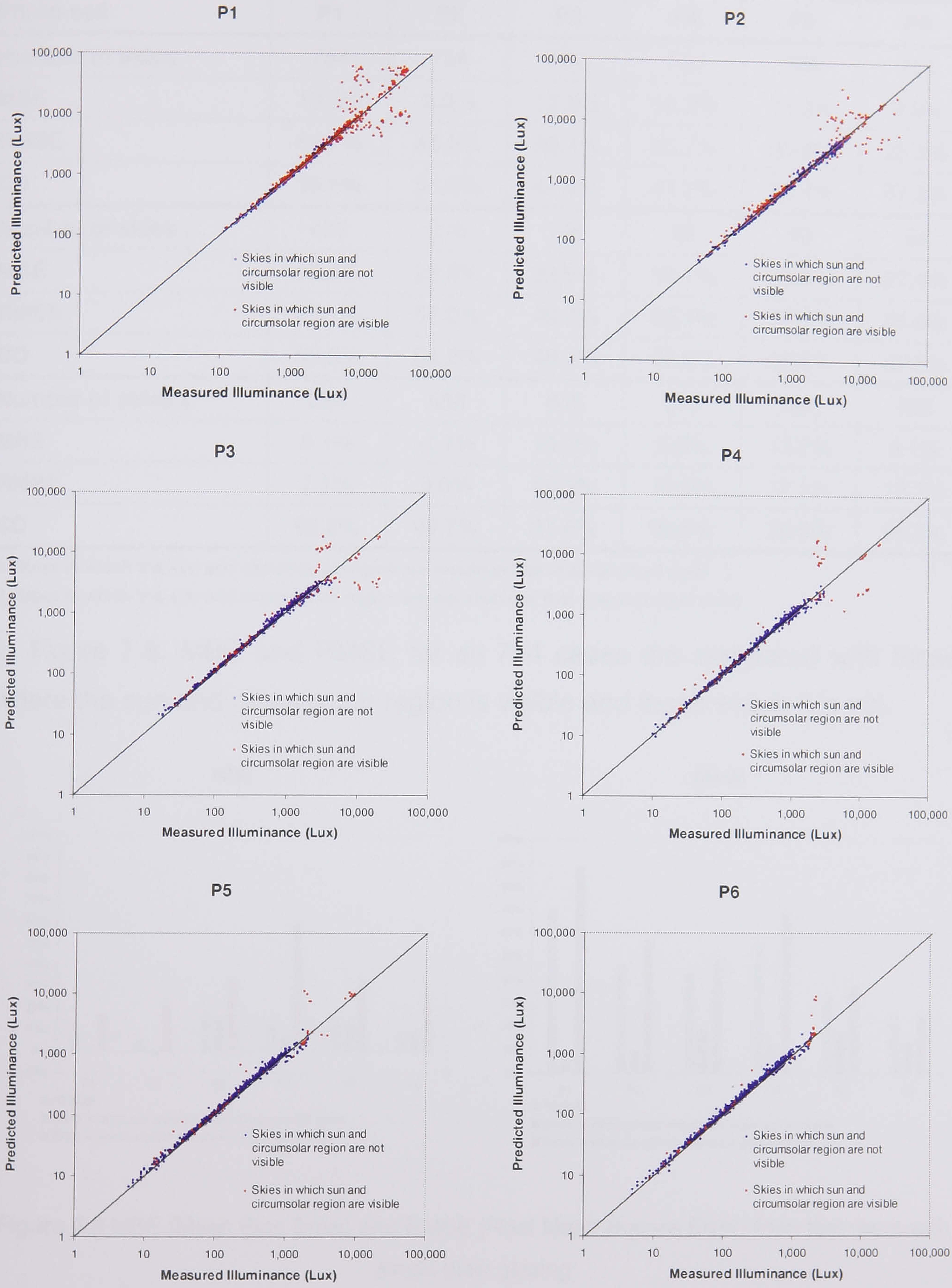


Figure 7.7 Comparison of predicted and measured illuminance from test room with single plain glazing, at photo-cells P1 to P6

In Table 7.1, MBE, RMSE and CD values for all 754 test cases are compared with those where the sun and circumsolar region is visible and those where it is not.

Table 7.1 MBE, RMSE and CD from test room with single plain glazing

Photo-cell	P1	P2	P3	P4	P5	P6
Number of skies	754	754	754	754	754	754
MBE	10.5%	5.3%	17.9%	12.3%	14.9%	9.5%
RMSE	69.7%	45.6%	42.4%	55.7%	33.4%	23.9%
CD	59.5%	54.6%	47.8%	47.2%	80.4%	67.6%
Number of skies $_1$	470	216	109	82	69	54
MBE	16.8%	22.6%	33.6%	59.1%	32.3%	27.4%
RMSE	88.1%	57.0%	49.3%	69.1%	37.0%	25.6%
CD	55.0%	56.3%	48.1%	47.9%	80.9%	67.8%
Number of skies $_2$	284	538	645	672	685	700
MBE	0.1%	-1.7%	15.2%	6.6%	13.2%	8.1%
RMSE	7.1%	9.0%	18.2%	12.0%	17.1%	13.1%
CD	98.6%	98.7%	97.5%	96.6%	95.9%	96.7%

1. Skies in which the sun and circumsolar region are visible at that measurement point
2. Skies in which the sun and circumsolar region are not visible at that measurement point

In Figure 7.8, MBE and RMSE for all 754 cases are compared with those where the sun and circumsolar region is visible and those where it is not.

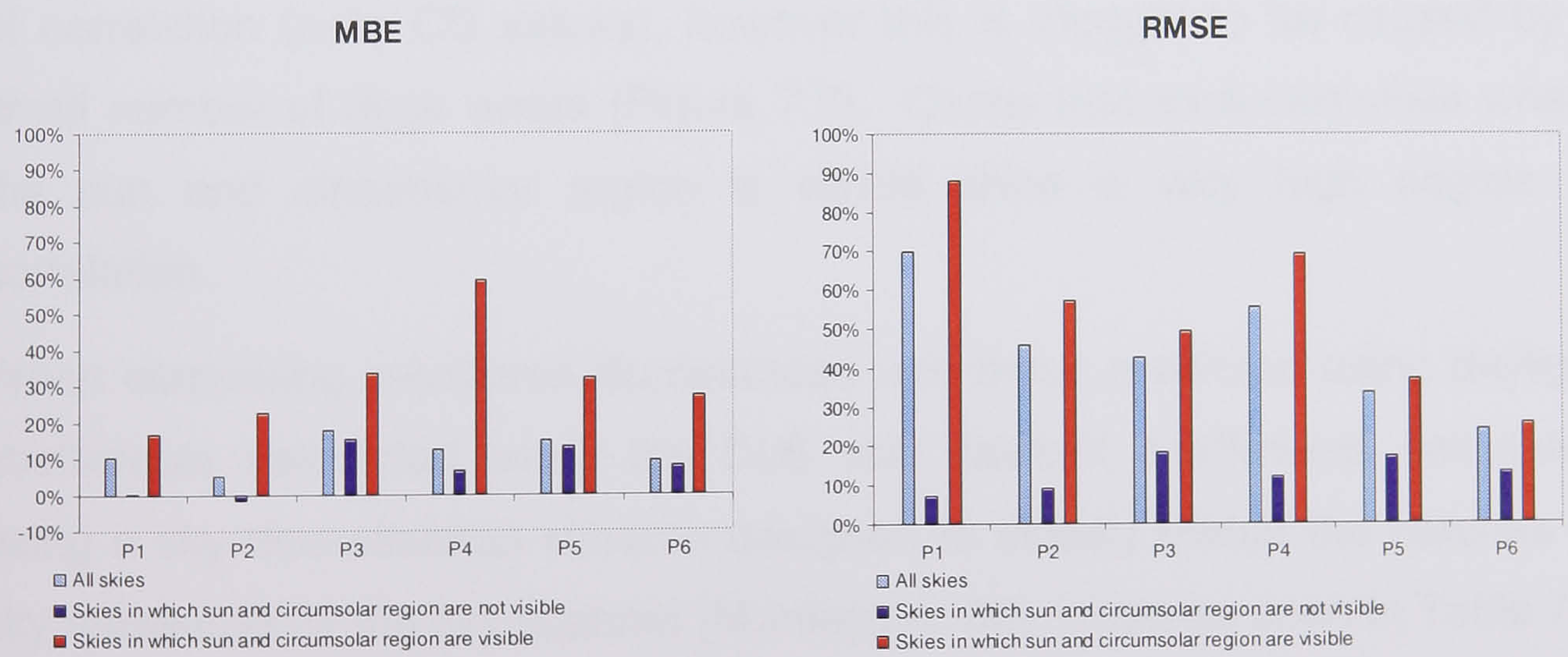


Figure 7.8 MBE (Mean Bias Error) and RMSE (Root Mean Square Error) from test room with single plain glazing

In Figure 7.6 it can be seen that there is a high frequency of low percentage errors, this is supported by a good correlation between measured and predicted values of illuminance (Figure 7.7), however it can also be seen that the DLS shows a tendency to over-predict. This may be caused by using the coarsely discretised measured sky luminance distribution. Although a high degree of sky discretisation was used when calculating coefficients, illuminance predictions were calculated using the 145-measured luminance values to provide the sky luminance distribution. This results in groups of discretised sky patches being assigned the same luminance value. This is not a problem when the whole sky hemisphere illuminates a measurement point because the sky luminance distribution was normalised to the Diffuse Horizontal Illuminance. However, results may be inaccurate when the measurement point is located inside a room and only the small number of patches visible though a window illuminate the measurement point.

In each of the plots in Figure 7.7, it can be seen that comparisons that produce large errors result from skies where the sun and circumsolar region is visible from the measurement point. It can also be seen that although some large errors are present in the data, there are a significant number of points coloured red that show a high degree of correlation over the full range of illuminance.

In Table 7.1, the comparisons of all 754 cases show only a moderate degree of correlation (note CD values), however this is thought to be caused by a small number of large errors (Figure 7.7). Cases that excluded skies where the sun and circumsolar region is visible show a very high degree of correlation.

When comparing measured illuminances with those predicted using daylight coefficients calculated using the DLS and daylight coefficients calculated using a sky discretisation scheme designed to closely match the patches of sky measured by the sky scanner [Mardaljevic 00], it can be seen in Table 7.2 that in general the results are very similar.

Table 7.2 Comparing MBE and RMSE values from two different daylight coefficient methods

Photo-cell	P1	P2	P3	P4	P5	P6
MBE[1]	10.5%	5.3%	17.9%	12.3%	14.9%	9.5%
RMSE[1]	69.7%	45.6%	42.4%	55.7%	33.4%	23.9%
MBE[2]	7.5%	6.0%	15.9%	4.5%	6.8%	-1.5%
RMSE[2]	69.6%	46.0%	42.1%	39.4%	29.3%	20.2%

1. Results of comparisons of measured values with values predicted by the DLS
2. Results of comparisons of measured values with values predicted by Mardaljevic

However, it can be seen that MBE values for photocells P4, P5 and P6, obtained when comparing values predicted by the DLS, show a higher bias error than those obtained by Mardaljevic. This is thought to result from differences in the method of sky discretisation and the method of assigning measured sky luminance values to individual patches of sky, as the photocells positioned further away from the window 'see' less of the sky area and so the effect of such variations will be greater.

7.3.4 Results obtained from the test room fitted with a diffuse reflecting light shelf

Values of illuminance predicted by the DLS, for the 294 test cases corresponding to the period when a diffuse reflecting light shelf was fitted in the second test room, were compared with measured values.

Figure 7.9 shows the Relative Error (RE) values plotted on frequency distribution histograms.

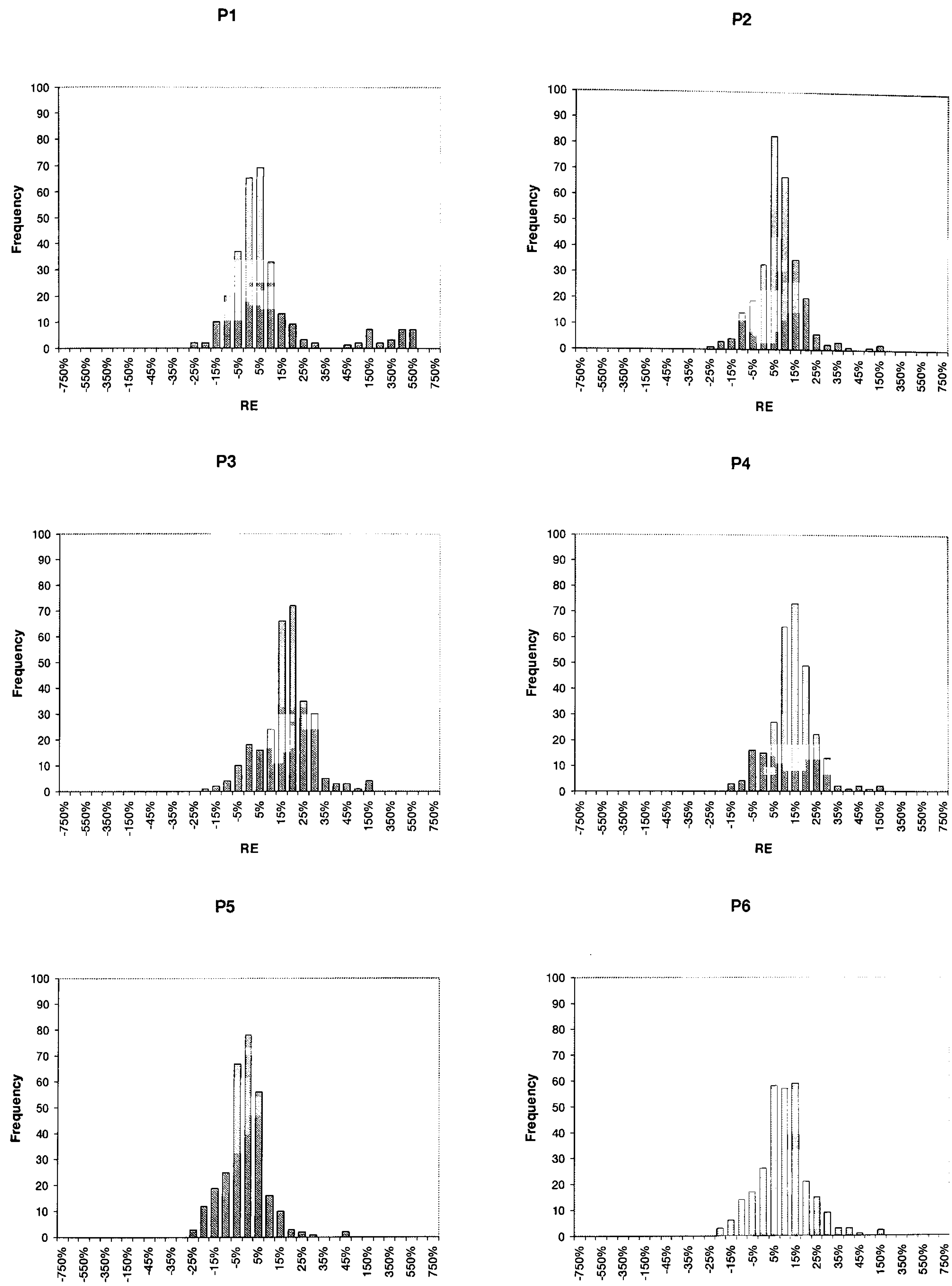


Figure 7.9 Frequency distribution of RE (Relative Error) from test room fitted with diffuse reflecting light shelf, at photo-cells P1 to P6

In Figure 7.10, the predicted values of illuminance are compared with measured values directly.

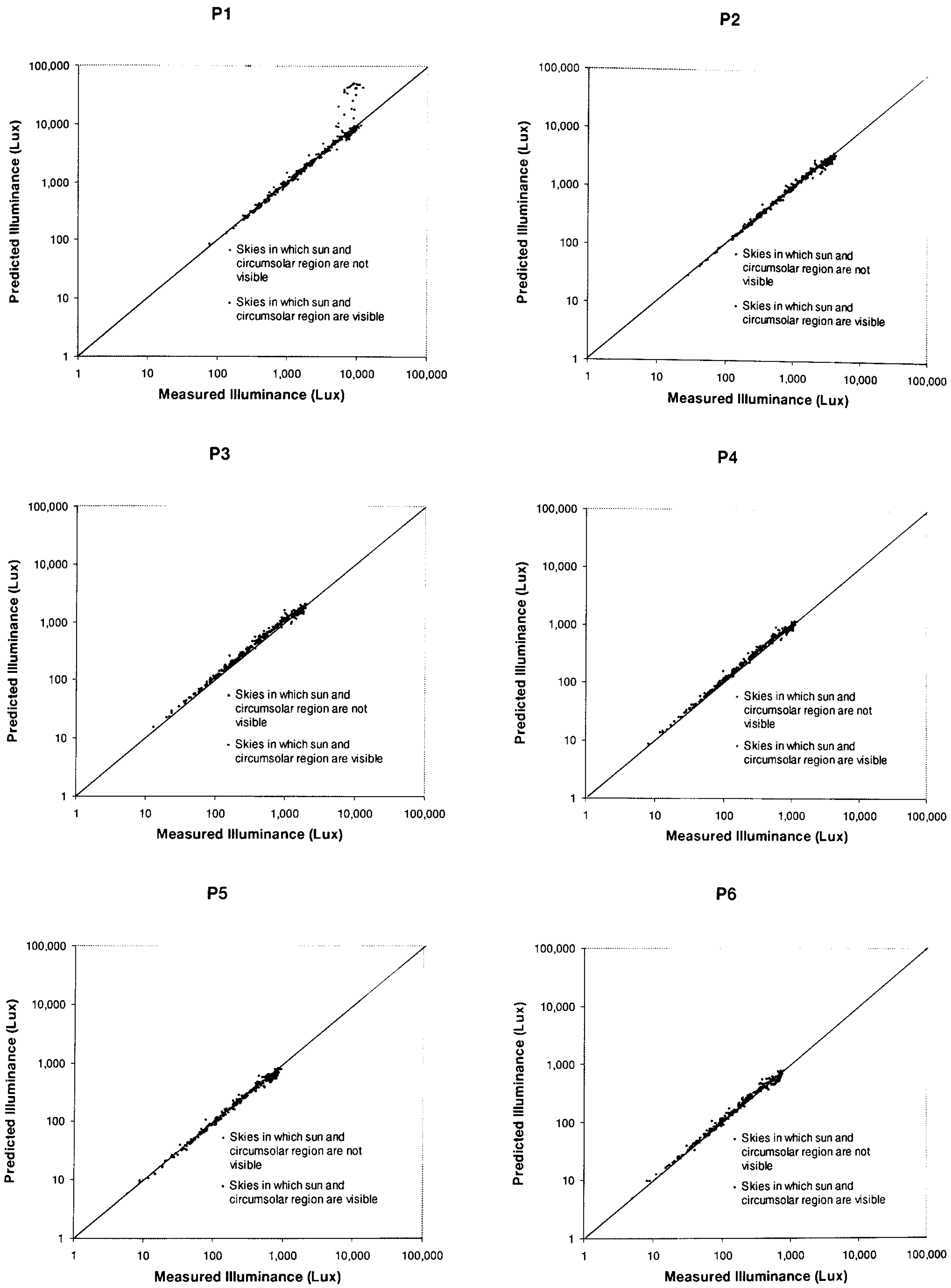


Figure 7.10 Comparison of predicted and measured illuminance from test room fitted with diffuse reflecting light shelf, at photo-cells P1 to P6

In Table 7.3, MBE, RMSE and CD values for all 294 test cases are compared with those where the sun and circumsolar region is visible and those where it is not.

Table 7.3 MBE, RMSE and CD from room fitted with diffuse reflecting light shelf

Photo-cell	P1	P2	P3	P4	P5	P6
Number of skies	294	294	294	294	294	294
MBE	27.3%	4.8%	14.8%	11.1%	-4.0%	6.7%
RMSE	102.4%	11.6%	19.1%	15.4%	10.2%	13.3%
CD	43.3%	97.1%	96.9%	97.3%	97.2%	96.7%
Number of skies $_1$	167	1	0	0	0	0
MBE	27.1%	0.0%	0.0%	0.0%	0.0%	0.0%
RMSE	102.3%	0.3%	0.0%	0.0%	0.0%	0.0%
CD	35.4%	-	-	-	-	-
Number of skies $_2$	127	293	294	294	294	294
MBE	0.2%	4.7%	14.8%	11.1%	-4.0%	6.7%
RMSE	4.2%	11.6%	19.1%	15.4%	10.2%	13.3%
CD	99.5%	97.1%	96.9%	97.3%	97.2%	96.7%

1. Skies in which the sun and circumsolar region are visible at that measurement point
2. Skies in which the sun and circumsolar region are not visible at that measurement point

The illuminance values in these test cases were measured during a short period at the end of April and the beginning of May. During this period, the position of the sun was such that it directly illuminated the photocell P1 (nearest to the window) on 167 occasions and photocell P2 on only one occasion. The other four photocells were not directly illuminated by the sun.

In Figure 7.11, MBE and RMSE for all 294 cases are compared with those where the sun and circumsolar region is visible and those where it is not.

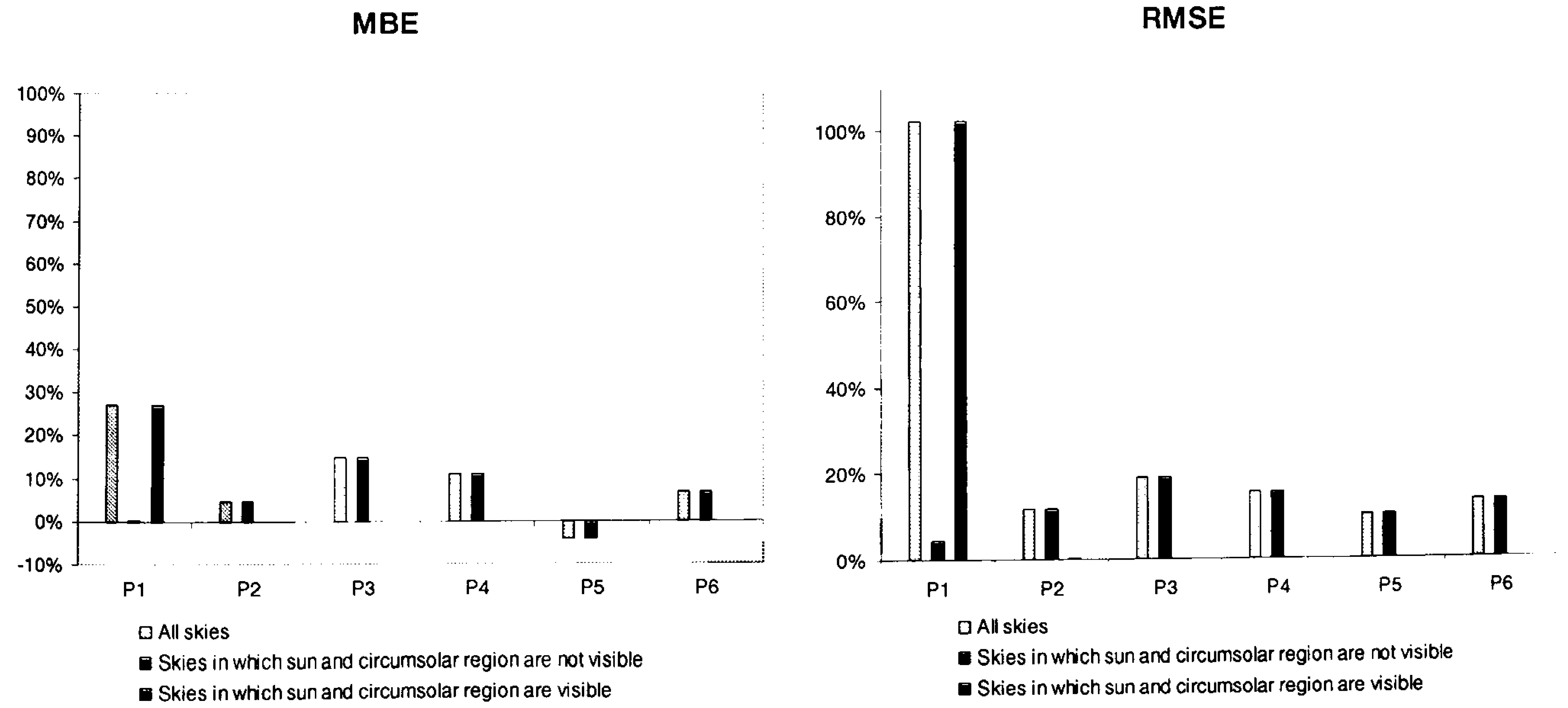


Figure 7.11 MBE (Mean Bias Error) and RMSE (Root Mean Square Error) from test room fitted with diffuse reflecting light shelf

In the comparison of predicted and measured illuminance of photocell P1 it can be seen, in both Figure 7.9 and Figure 7.10, that the large errors represent an over-prediction by the DLS. The relatively small number of test cases used in these comparisons were measured over a very short time period during which the path of the sun across the sky changed very little. It is thought that this resulted in similar errors in the placement of the sun being repeated, when the coefficient corresponding to the nearest sky patch was used to calculate the direct solar component of illuminance. This resulted in an over prediction in each case, giving high values of MBE and RMSE (Table 7.3).

7.3.5 Results obtained from the test room fitted with a specular reflecting light shelf

Values of illuminance predicted by the DLS, for the 65 test cases corresponding to the period when a specular reflecting light shelf was fitted in the second test room, were compared with measured values. Figure 7.12 shows the Relative Error (RE) values plotted on frequency distribution histograms.

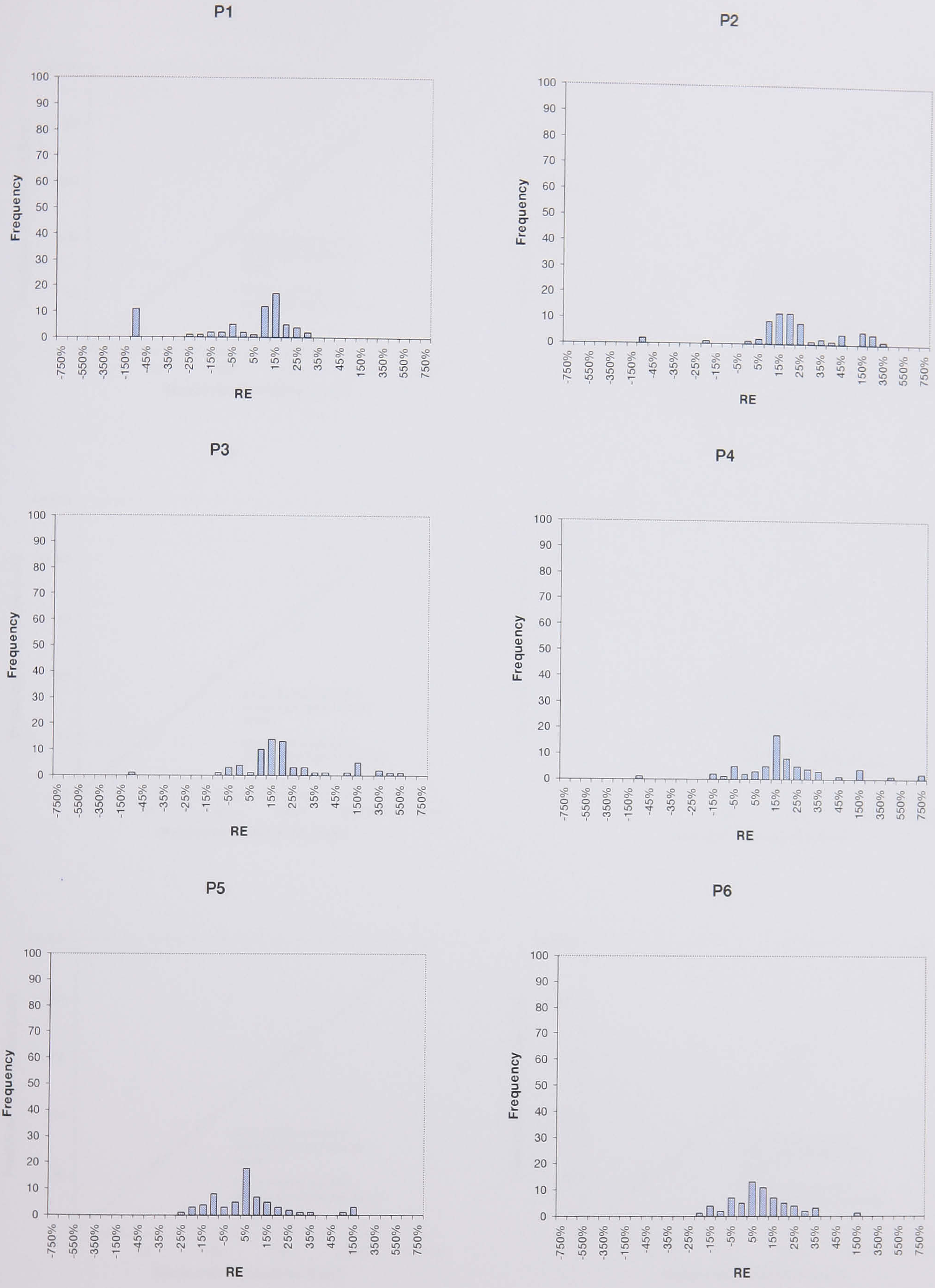


Figure 7.12 Frequency distribution of RE (Relative Error) from test room fitted with specular reflecting light shelf, at photo-cells P1 to P6

In Figure 7.13, the predicted values of illuminance are compared with measured values directly. The illuminance values in these test cases were measured during a short period in November.

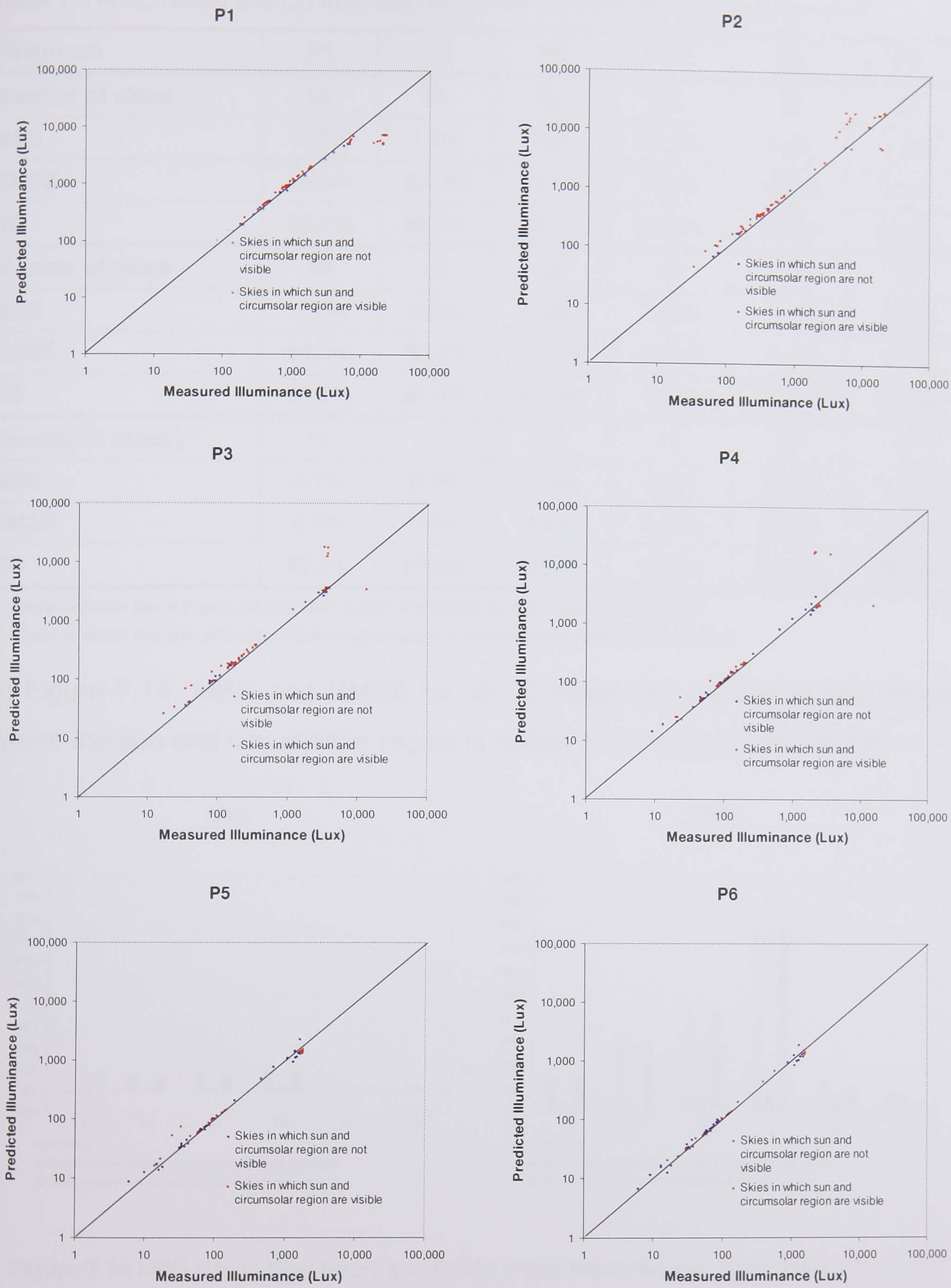


Figure 7.13 Comparison of predicted and measured illuminance from test room with specular reflecting light shelf, at photo-cells P1 to P6

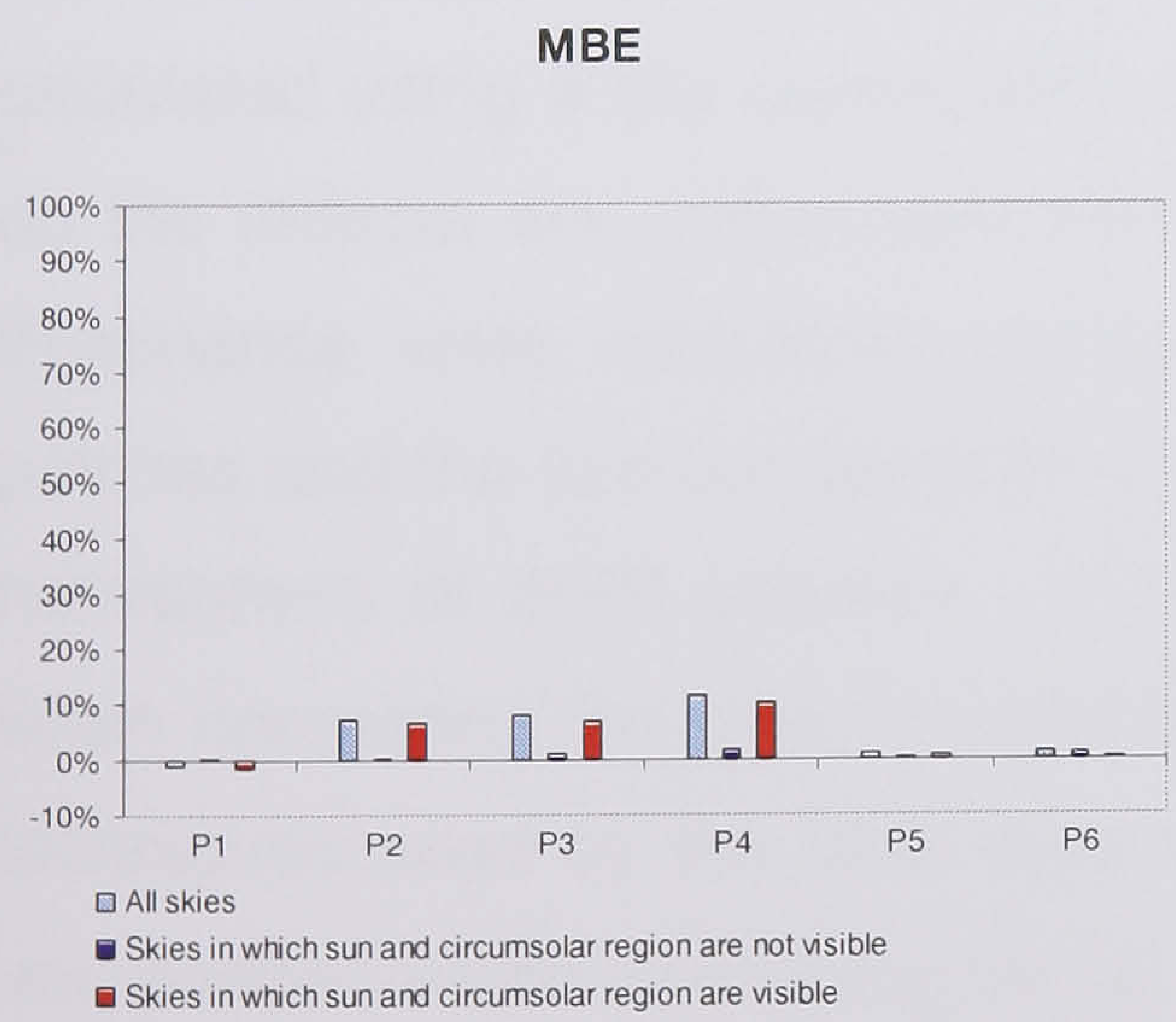
In Table 7.4, MBE, RMSE and CD values for all 65 test cases are compared with those where the sun and circumsolar region is visible and those where it is not.

Table 7.4 MBE, RMSE and CD from test room fitted with specular reflecting light shelf

Photo-cell	P1	P2	P3	P4	P5	P6
Number of skies	65	65	65	65	65	65
MBE	-1.3%	7.2%	7.9%	11.7%	1.0%	1.3%
RMSE	14.5%	30.2%	43.5%	79.1%	12.0%	7.1%
CD	39.8%	68.3%	45.1%	25.7%	60.9%	39.8%
Number of skies $_1$	48	58	42	34	29	18
MBE	1.4%	6.8%	7.0%	10.2%	0.7%	0.2%
RMSE	14.3%	30.1%	43.3%	78.8%	11.0%	2.9%
CD	80.5%	66.4%	23.7%	6.5%	99.6%	80.5%
Number of skies $_2$	17	7	23	31	36	47
MBE	0.1%	0.4%	0.9%	1.5%	0.3%	1.1%
RMSE	2.7%	2.5%	4.6%	6.7%	4.8%	6.5%
CD	99.7%	99.9%	97.8%	94.4%	92.8%	99.7%

1. Skies in which the sun and circumsolar region are visible at that measurement point
2. Skies in which the sun and circumsolar region are not visible at that measurement point

In Figure 7.14, MBE and RMSE for all 65 cases are compared with those where the sun and circumsolar region is visible and those where it is not.



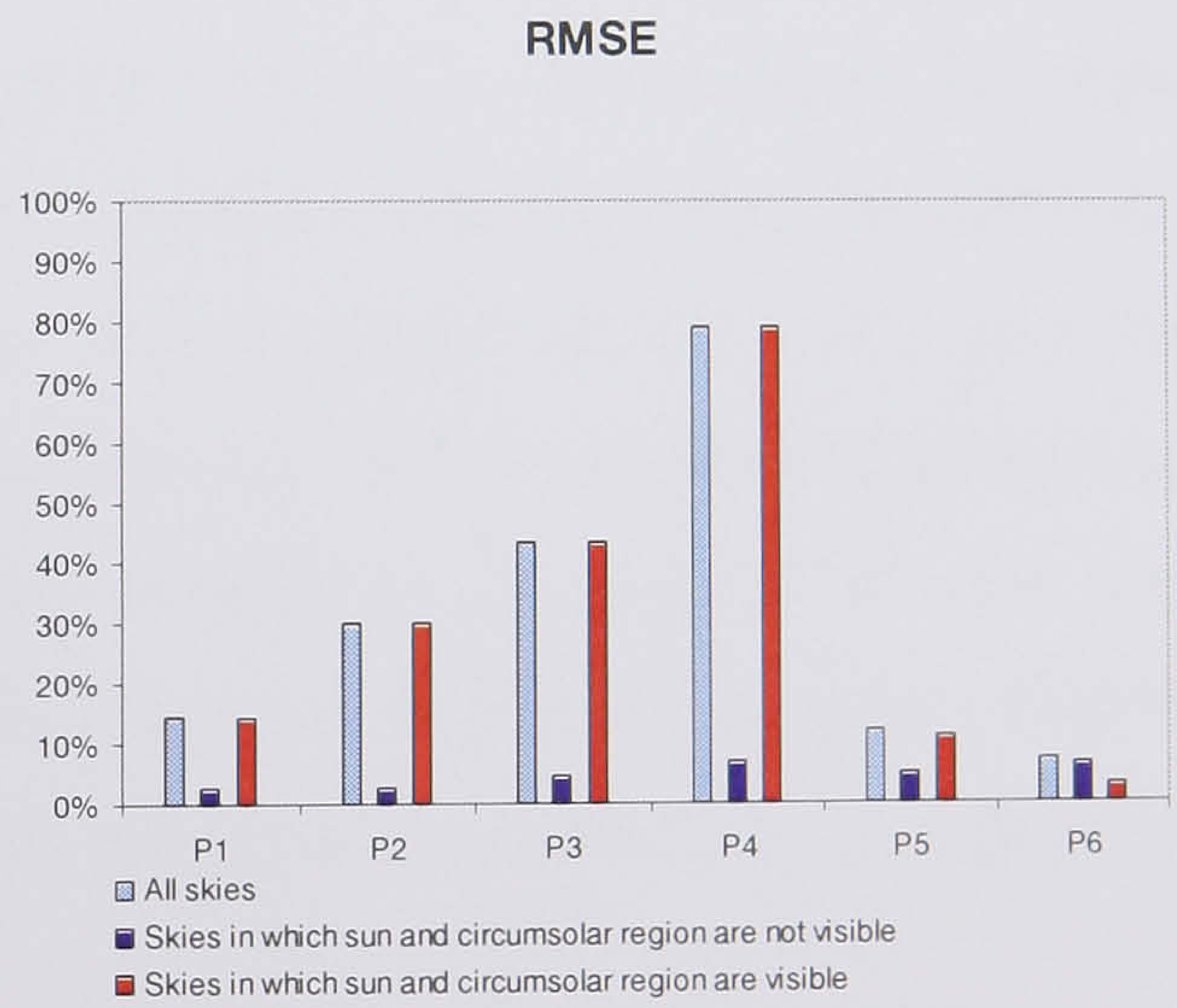


Figure 7.14 MBE (Mean Bias Error) and RMSE (Root Mean Square Error) from test room fitted with specular reflecting light shelf

It can be seen in Figure 7.13 that the predicted and measured values of illuminance show a high degree of correlation. However, due to the small number of test cases, a small number of very large errors has resulted in high values of MBE and RMSE. This can be seen in the values for photocell P4 in Table 7.4.

7.4 Varying the degree of sky discretisation

The degree of sky discretisation can effect both the performance and accuracy of the DLS, as described previously in section 7.2. In this section, the relative accuracies resulting from different degrees of discretisation are compared.

In order to examine the effect of varying the degree of discretisation, the DLS was used to predict levels of illuminance in the BRE test room fitted with single plain glazing, during the daylight hours of a typical year, a Test Reference Year[1] (TRY) [Petherbridge 83], resulting in 4739 sets of illuminance values. The simulation was repeated using different degrees of sky discretisation and the effect on the four components of illuminance, the direct sky component, the direct solar component, the indirect sky component and the indirect solar component, compared.

To examine the effect on the direct sky component and the direct solar component, values of illuminance were calculated using sky hemispheres of 40, 160, 640 and 2560 patches and the two components compared with those calculated using a sky hemisphere of 10240 patches. To examine the effect on the indirect sky component and the indirect solar component, values of illuminance were calculated using sky hemispheres of 40, 160 and 640 patches and the two components compared with those calculated using a sky hemisphere of 2560 patches. A higher degree of discretisation was used when comparing the direct components because it was anticipated that the techniques used by the DLS were more sensitive to variations in patch size and position when calculating these.

Due to the very large range of values of predicted levels of illuminance, variations in each of the four components resulting from using different degrees of discretisation were compared with the total predicted illuminance at each instance in order to examine the effective magnitude of the variations.

The Mean Absolute Error, the mean of the errors obtained when comparing the absolute values of each component of illuminance, expressed as a

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[1] TRY Kew 1986.

percentage of the total illuminance from all four components, is shown in Figure 7.15.

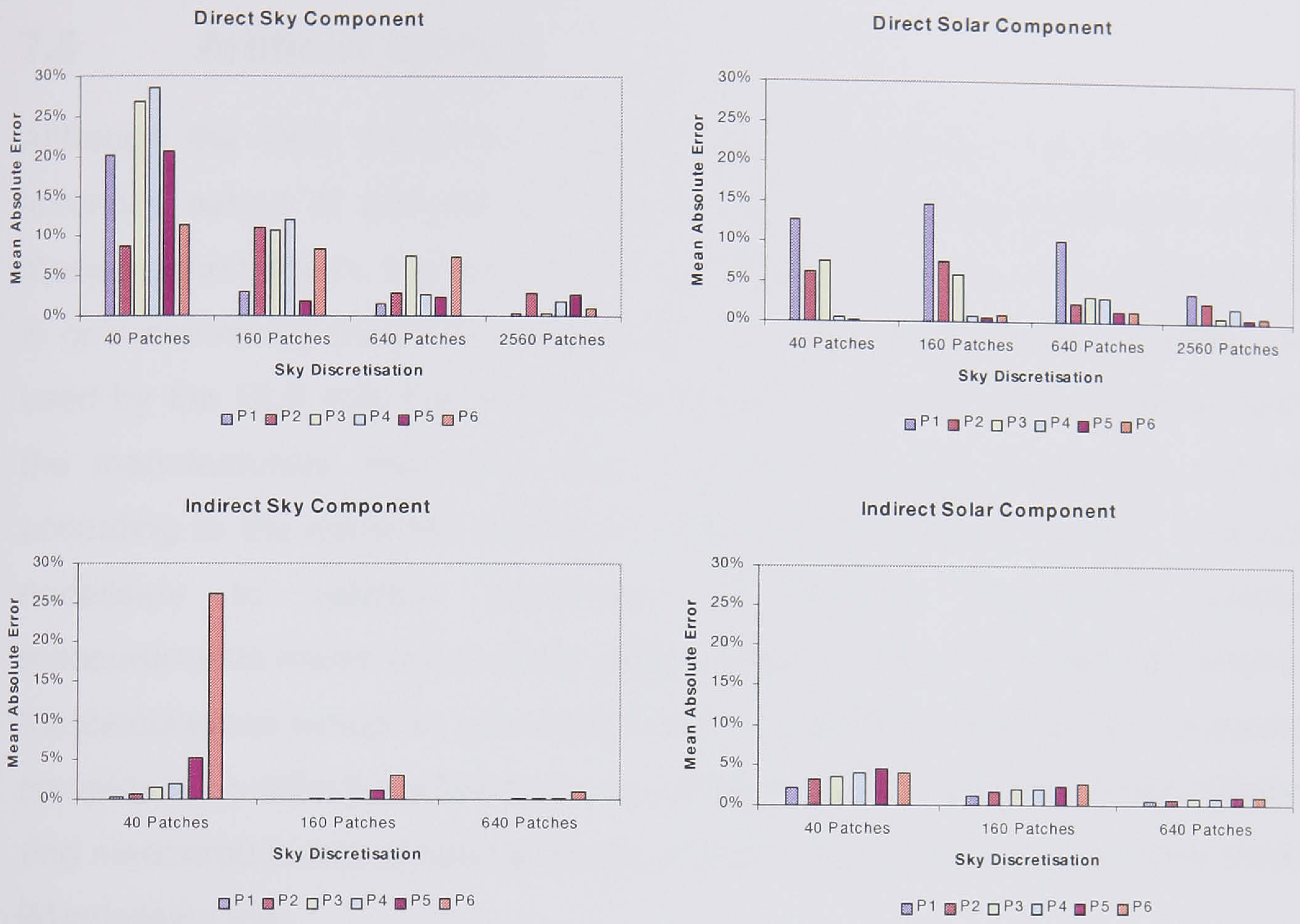

Figure 7.15 Mean Absolute Error expressed as a percentage of total illuminance, at photo-cells P1 to P6

In each chart of Figure 7.15 it can be seen that the trend is for the magnitude of the errors to decrease as the degree of discretisation is increased.

If the errors in the indirect sky component and the indirect solar component are examined, for each degree of discretisation it can be seen that the magnitude of the errors tend to increase the further the measurement point is away from the window. The further a measurement point is away from the window, the greater is the area of internal surfaces off which light can be reflected onto the measurement point, particularly after a single reflection (which is the most significant) and hence the greater the sensitivity to variations in indirect illuminance.

It can be seen that, for this room configuration, if the degree of discretisation used to calculate the direct components was set to 2560 patches rather than 10240 patches, and the degree of discretisation used to calculate the indirect components was set to 160 patches rather than 2560 patches, the relative errors would increase by less than 5%.

7.5 Artificial lighting

Although the DLS calculates Artificial Light Coefficients, which relate the luminous output of artificial light sources to the resulting illuminance at the measurement points, the RADIANCE luminaire models are used unaltered. It is only necessary therefore to establish that when the luminaire models are used by the DLS that the levels of illuminance predicted are consistent with the manufacturers measured data, and that they are turned on and off according to the expected behaviour of the light switching models. It is not necessary to validate predictions of artificial illumination against measurements made in a realistic setting because the only additional factor in the calculations would be inter-reflections. The ability of RADIANCE to model complex inter-reflections has been established by the comparison of predicted and measured levels of natural illuminance in this research, and another study [Mardaljevic 95].

7.5.1 Light output distribution

Two types of light source were modelled inside a fully enclosed 10m x 10m x 3m black (non-reflecting) room and the light output predicted at points along two lines (at the floor level and 1.5m above the floor). The predicted illuminance values were compared with values calculated using Equation 2-2, described in Chapter 2 section 2.3.1. To make comparison easier, the positions of the measurement points were chosen to coincide with the angles at which the manufacturers photometric data was measured.

Figure 7.16 shows the light distribution from a spotlight placed at the ceiling level in the centre of the room. It can be seen that the predicted and calculated values are identical, and that doubling the distance from the light source to the measurement point decreases the level of illuminance four fold.

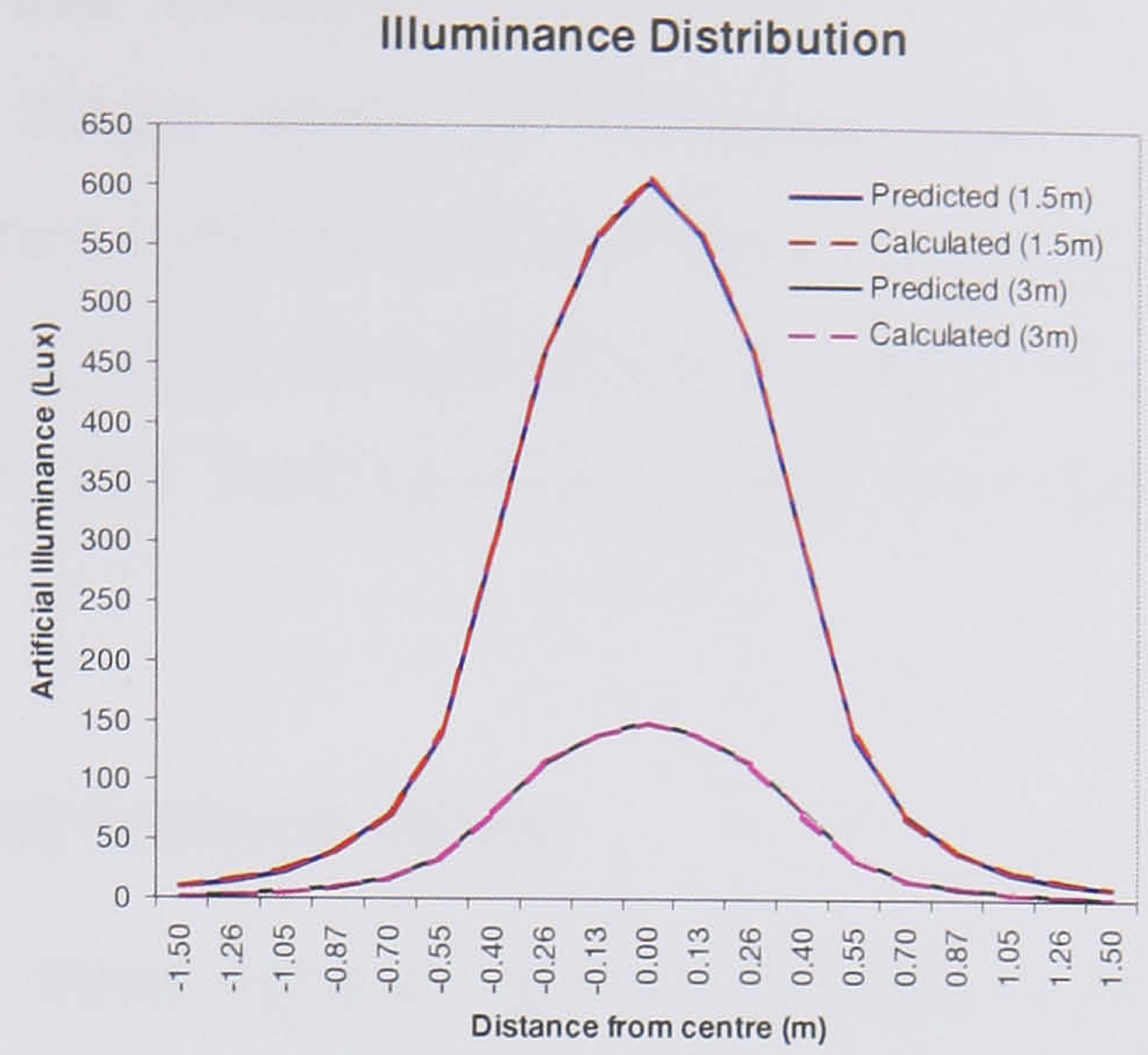

Figure 7.16 Illuminance distribution from a spotlight

Figure 7.17 shows the light distribution from a luminaire (a 1.2 m fluorescent tube in an aluminium housing), placed in the same position as the spotlight in the previous example, perpendicular to the two lines of measurement points.

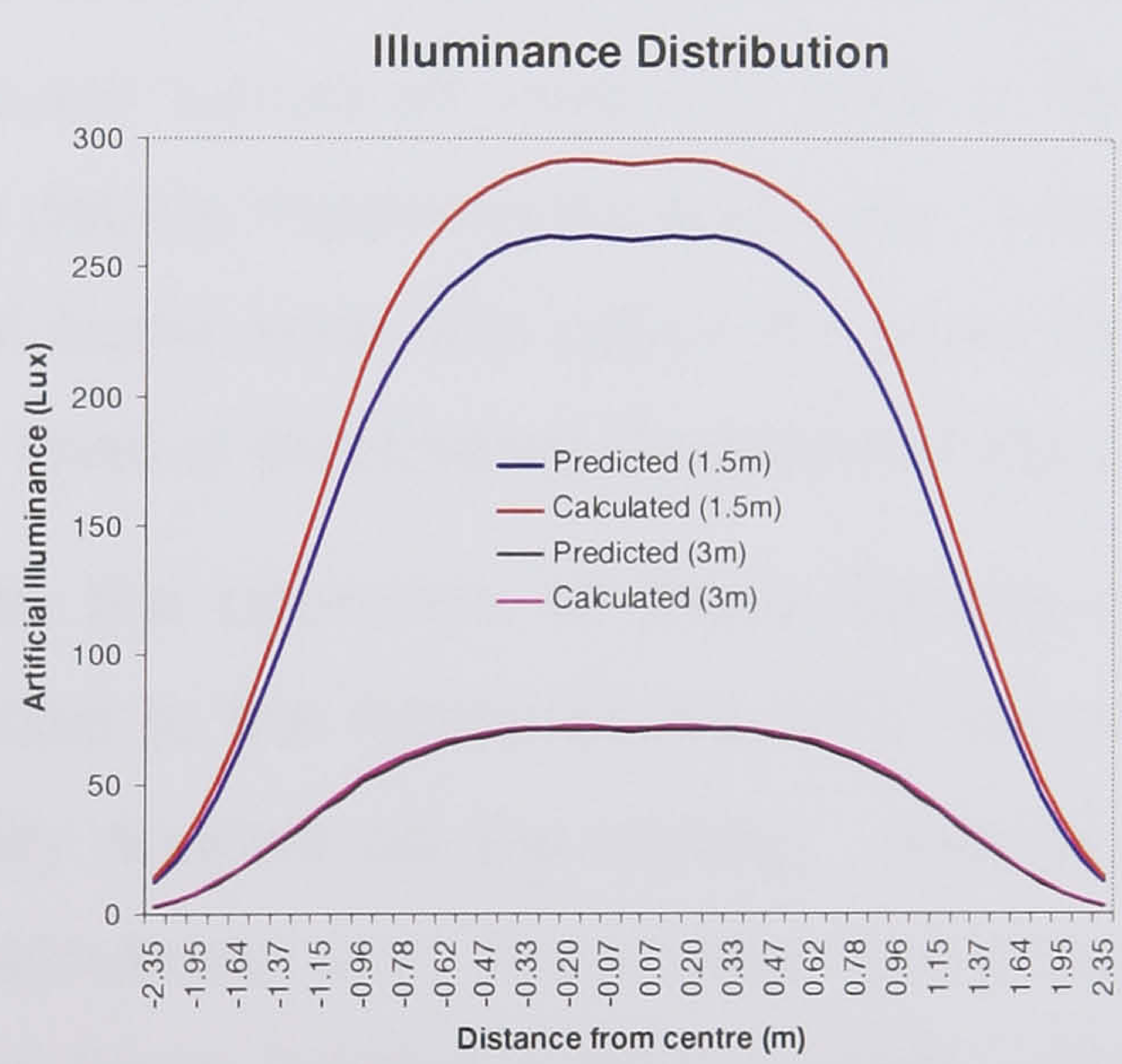

Figure 7.17 Illuminance distribution from a luminaire

It can be seen in this example that there is a difference between the predicted and calculated values. The light output distribution of the luminaire measured by the manufacturer is used by RADIANCE to predict the amount of light emitted in a given direction. It is measured using far-field photometry, i.e. at a distance such that the luminaire is taken to behave as a single point of light (a point source). When this distribution is used by RADIANCE, it is applied to a self-luminous surface the same size as the luminaire. During the RADIANCE simulation, measurement points close to the luminaire receive light from different parts of this surface. Differences in the angles of incidence, compared to the single angle of incidence from a point source, and differences in distance between parts of the surface and measurement point, cause the illuminance to be calculated inaccurately. As the distance between the luminaire and the measurement point increases, this discrepancy decreases.

7.5.2 Control of artificial lights

The DLS provides three lighting control models, manual switching, single threshold photoelectric switching and double threshold photoelectric switching. The manual-switching algorithm, which attempts to model human behaviour, is based on the probability that a person entering a room will switch lights on. Repeated simulation of the same time-period will result in different patterns of light switching. With single threshold photoelectric switching, lights are turned on when the level of illuminance falls below the threshold and lights are turned off when the level of illuminance rises above the threshold. With double threshold photoelectric switching, lights are turned on when the level of illuminance falls below the lower threshold and lights are turned off when the level of illuminance rises above the upper threshold.

In order to illustrate the operation of these lighting control models, three luminaires were added to the model of the BRE test room fitted with single plain glazing, equally spaced on the ceiling. Natural and artificial lighting coefficients were calculated, and illumination predictions for the Kew TRY calculated using the three lighting control models. Figure 7.18 shows the illumination by natural and artificial light during a typical three-day period, when the artificial lights are controlled by the manual switching algorithm (equation (6-1)) from 8am until 6pm.

On the first day the level of natural illuminance is high at the start of the occupancy period, lights are not turned on until late afternoon when the level of natural illuminance falls. On the second day the level of natural illuminance is much lower, lights are switched on at the start of the occupancy period and remain on all day. On the third day, the lights remain on all day, despite increased levels of natural illuminance during the late morning period.

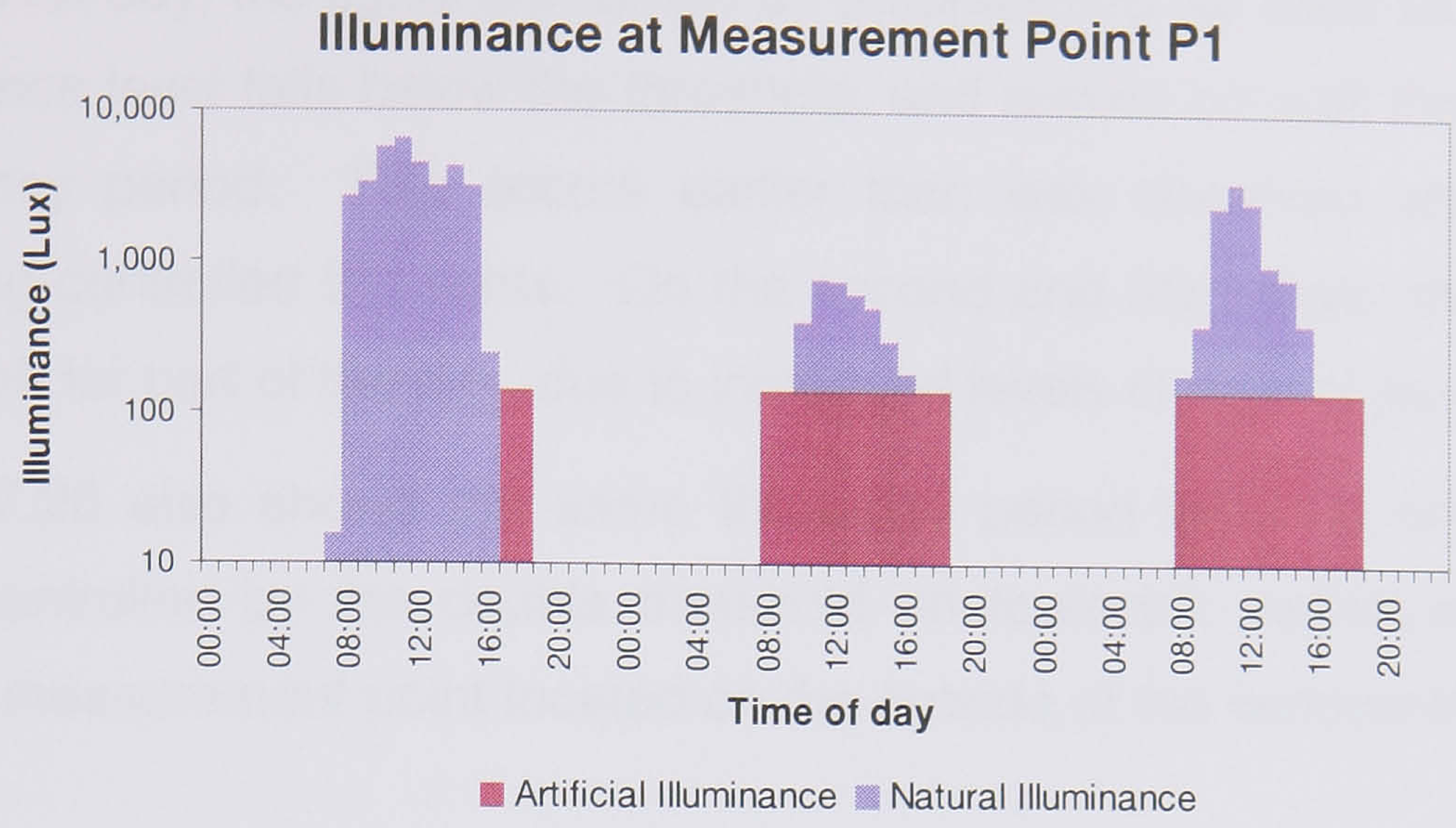

Figure 7.18 Artificial lights controlled by manual switching

Figure 7.19 shows the same three-day period with the artificial lights being controlled by the single threshold photoelectric switching algorithm, using a measurement point located on the outside of the window frame as the sensor.

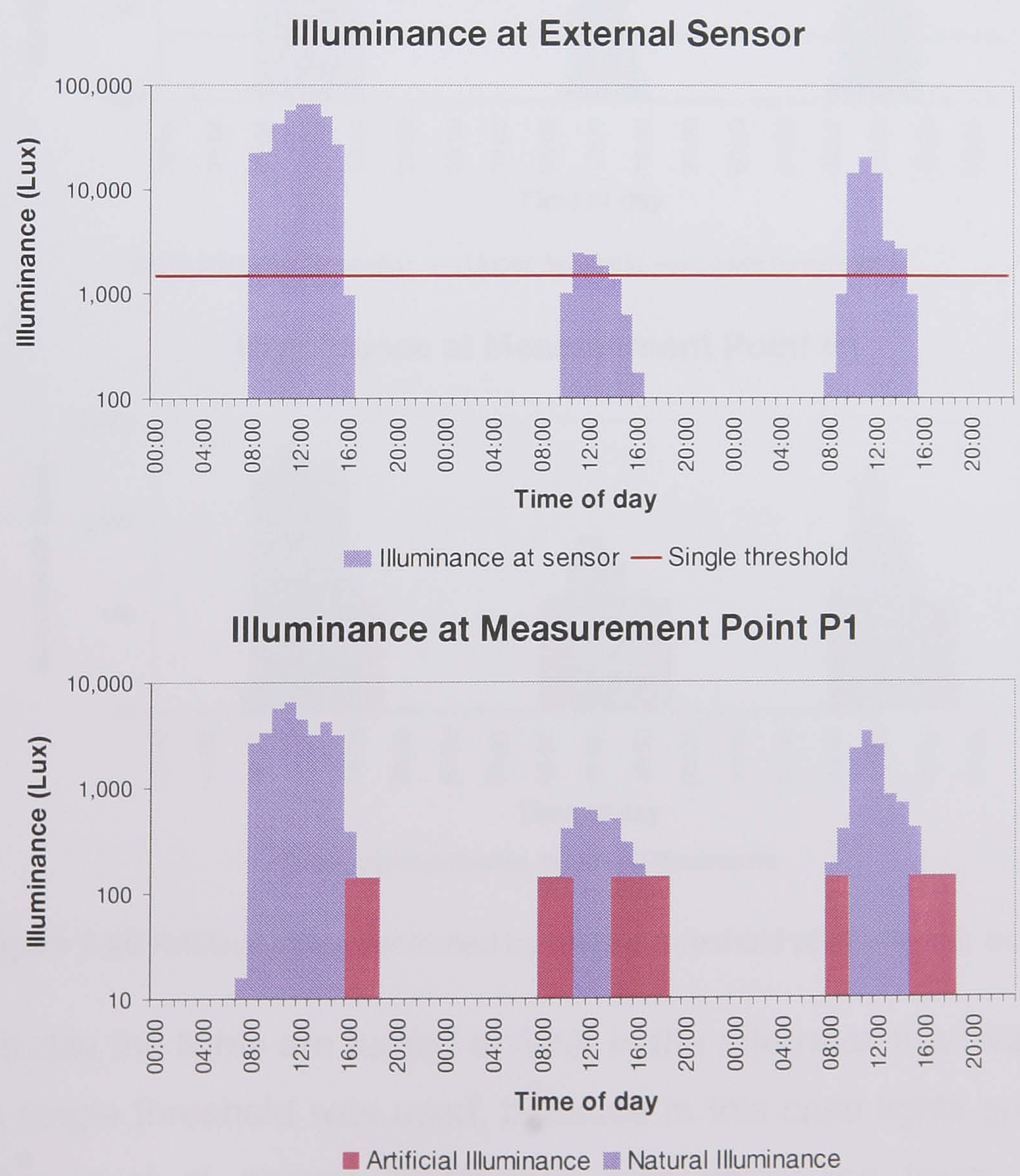

Figure 7.19 Artificial lights controlled by single threshold photoelectric switching

On the first day, the lights are turned on automatically as soon as the natural illuminance level falls below the threshold, and remain on until the end of the occupancy period. This occurs earlier than was observed when manual switching controlled the lights. On the second and third days, the lights are turned off for part of the day, due to increased levels of natural illuminance.

Figure 7.20 also shows the same three-day period with the artificial lights being controlled by the double threshold photoelectric switching algorithm, using a measurement point located on the outside of the window frame as the sensor.

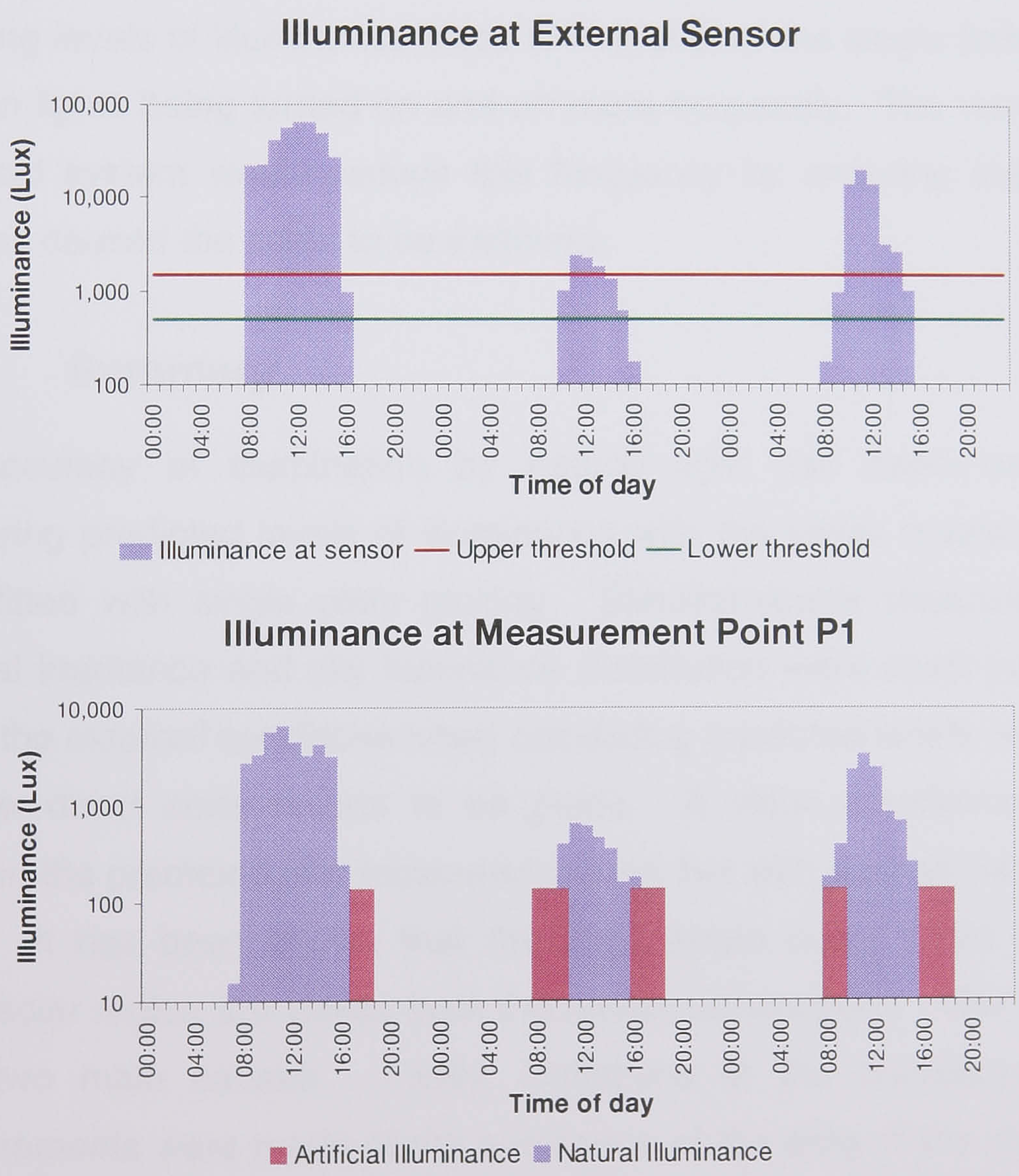

Figure 7.20 Artificial lights controlled by double threshold photoelectric switching.

On each day the lights are turned on later in the afternoon than was observed when a single threshold was used, because in this case lights are turned on when the level of natural illuminance falls below the lower of the two thresholds, set lower than the single threshold in the previous example. On the second and third days the lights are turned off at the same times when the level of natural illuminance rises above the upper threshold, which was set the same as the single threshold in the previous example.

The TRY provides hourly averaged values of external illuminance, which were used in these examples to determine the levels of natural illuminance. This did not permit the effect of rapidly changing levels of natural illuminance to be demonstrated clearly. It is anticipated that if external illuminance data measured at much shorter intervals were to be used, greater differences between the patterns of light switching resulting from the use of single and double threshold photoelectric switching would be observed. Rapidly changing levels of illuminance close to the level of the single threshold would result in lights being turned on and off more frequently. The use of a double threshold system would reduce this frequency by ensuring that only large changes caused the lights to be switched.

7.6 Summary

The accuracy of illumination by natural light has been examined, by comparing predicted levels of illuminance with the levels measured in a test room fitted with single plain glazing. Simultaneously measured levels of external irradiance and sky luminance distribution were used by the DLS to model the external conditions when calculating predicted levels of illuminance, to allow direct comparisons to be made. A close correlation was found between the predicted and measured values, but with a small number of large errors. It has been shown that the large errors occur when the sun and circumsolar region are visible from the measurement point. This is thought to have two main causes. Firstly, limitations in the accuracy with which measurements were made of the luminance of the area of the sky containing the sun and circumsolar region. This provided a poor model of the external conditions on some occasions. Secondly, the effective displacement of the sun position caused by using the coefficients calculated for a patch of discretised sky when calculating solar luminance rather than coefficients calculated for the exact sun position at each time step. Selectively increasing the degree of sky discretisation in the areas close to the edges of windows may significantly reduce this effect. Similar results are obtained when values were compared for the second test room, when fitted with a diffuse or specular reflecting light shelf.

When the effect of varying the degree of sky hemisphere discretisation was examined, it has been shown that patch size has greater effect on the accuracy of the predicted direct components of illuminance than on the indirect components. Comparisons were made, using different degrees of sky hemisphere discretisation, with a 10240-patch sky when calculating direct components and a 2560-patch sky when calculating indirect components. It was found that reducing the degree of discretisation to 2560 patches when calculating direct components and 160 patches when calculating indirect components results in a reduction in accuracy of less than 5%. The results suggest that these levels of discretisation provide a good compromise between the times required to calculate coefficients and predictions, and the accuracy of those predictions. However, these tests should be repeated for a wide range of different building configurations to confirm this recommendation.

When illumination by artificial lights was examined, it was shown that the light output distribution closely matched that defined by the manufacturer when predicted at floor level (3m below the luminaire). However, predictions made closer to the light source (1.5m below the luminaire) are less accurate. This is thought to be due to the manufacturers photometric data being equivalent to that which would be obtained from an idealised point source, where as RADIANCE models the correct size of the luminaire.

When the switching of artificial lights by lighting control models was examined, it has been shown that when controlled by the manual switching algorithm the pattern of light switching is consistent with the behaviour predicted. It has also been shown that when controlled by the photoelectric switching algorithms, lights are switched on and off at the correct times when the externally measured level of illuminance rises above or below the relevant threshold.

Chapter

8 Conclusions

8.1 Overview

This research has resulted in the development of a lighting design tool, the Dynamic Lighting System (DLS), which is able to predict time-varying illumination. The DLS is a platform independent computer program that is able to predict the full range of illumination from sunlight, daylight and artificial lights. It places no theoretical limitation on the complexity of the building geometry, or external structures. The building can be located anywhere in the world and have any orientation. Locally gathered weather data can be used to control the characteristics of natural light, to closely replicate local conditions. The DLS provides architects and lighting engineers with the ability to quantitatively evaluate the dynamic behaviour of complex lighting designs incorporating both natural light and light from complex luminaires controlled by a range of lighting control systems. The program can predict the levels of illumination and the electrical energy consumption that could be expected over any time-period. This information can then be used to compare different lighting designs to maximise the use of natural light whilst at the same time providing a stimulating and comfortable environment for the occupants. In addition to calculating electrical energy consumption, the number of hours the lights are turned on and the number of times they are switched on and off can be used to estimate wear-and-tear.

The DLS can be used to address other common lighting problems, such as glare on computer screens, because of its ability to predict illuminance on any surface and with any orientation. This ability can also be used to ensure that works of art in an art gallery are not exposed to excessive illumination, by calculating cumulative illumination (Lux hours).

8.2 General conclusions

The levels of natural illuminance predicted by the DLS showed good agreement with the values measured in the BRE test room fitted with single plain glazing. The comparisons showed a high degree of correlation but with a relatively small number of large errors. The presence of these large errors resulted in a Root Mean Square Error (RMSE) of between approximately 23% and 70% across the points measured. The DLS showed a tendency to over-predict, indicated by a Mean Bias Error (MBE) of between approximately 5% and 18%. These large errors were shown to occur when the sun and circumsolar region were visible from the measurement points. Similar results were found when predictions for the second test room, fitted with two different types of light shelf, were examined.

The levels of artificial illuminance predicted by the DLS were found to be identical to those calculated using the manufacturers photometric data when a spotlight was modelled in a black (non-reflecting) fully enclosed room. When a more complex luminaire was substituted for the spotlight, differences were found between the predicted and calculated values. The difference between the predicted and calculated values was approximately 4% at a point 3m from the luminaire and approximately 10% at a point 1.5m from the luminaire. This discrepancy is thought to be because the photometric data quoted by the manufacturers assume that the luminaire acted as a point source, with RADIANCE the true shape of the luminaire is modelled.

The patterns of light switching resulting from using three different light switching algorithms; manual switching, single threshold photoelectric switching and double threshold photoelectric switching, were consistent with expected behaviour. However, due to the non-deterministic basis of the manual-switching algorithm, it was not possible to establish conclusively that the algorithm functioned correctly. The two photoelectric switching algorithms were found to switch the lights at the levels of illuminance set. However, due to the Test Reference Year (TRY) containing hourly averaged illuminance data it was not possible to fully investigate differences in behaviour that would result from rapidly changing levels of natural illuminance.

The computer programming language Java was found to be an ideal language with which to develop the DLS. The DLS runs without modification or needing to be re-compiled on a Personal Computer (PC) under the Microsoft Windows and Linux operating systems, and on a Sun Workstation under the Solaris (UNIX) operating system. It was not possible to calculate coefficients when running under Microsoft Windows due to the PC version of RADIANCE (available at the time) being unsuitable.

8.3 Suggestions for further work

The comparisons of predicted and measured illuminance, described in chapter 7 indicate that the DLS produces a relatively small number of large errors when the measurement point is directly illuminated by the sun and circumsolar region. Further work is needed to identify the precise cause of these errors, to develop strategies to avoid them and thus to ensure that the DLS is able to model natural illuminance that includes direct illumination by the sun.

The comparisons of predicted and measured illuminance, described in chapter 7 indicate that the DLS over-predicts illuminance by between 5% and 18%. More work is needed to establish what might be the cause of this over-prediction.

The comparisons between different light switching algorithms, described in chapter 7 were carried out using a TRY that contained hourly averaged values of illuminance. These tests should be repeated using illuminance data measured over much shorter time intervals to investigate the behaviour of the light switching algorithms when the level of natural illuminance is changing rapidly.

The DLS uses a fixed degree of sky discretisation when calculating coefficients. Dynamically varying the degree of discretisation, when calculating coefficients, should be investigated. The aim would be to increase the resolution of patches close to the edge of windows, to reduce the instances where inaccurate placement of the sun causes large prediction errors.

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Appendix

A Equations

A.1 Introduction

This appendix starts by describing the luminous efficacy model equations, used to convert measured values of irradiance into illuminance. The Perez All-Weather Sky Model equations that are used to obtain realistic patterns of sky luminance distribution are then described. Finally, the equations that are used to calculate the position of the sun is calculated for a given world location, time and date are described.

A.2 Luminous efficacy model

The irradiance values obtained from weather data describe the total energy ($W/sr/m^2$) from the sun and sky, including both the visible and invisible parts of the electromagnetic spectrum. A luminous efficacy model[1] is used to isolate the visible portion of the spectrum ($Lm/sr/m^2$).

A.2.1 Direct Normal Illuminance

The Direct Normal Irradiance (*Ees*) is converted to Direct Normal Illuminance (*Evd*) by

$$Evs = K_B Ees \qquad Lux \tag{A-1}$$

Where K_B is the direct luminous efficacy

If Solar Altitude $\gamma_S \leq 50^0$ then

$$K_B = 62.134 - 0.75885\gamma_S + 0.27749\gamma_S^2 - 0.12108\gamma_S^3 + 0.0002052\gamma_S^4 - 1.2278\times10^{-6}\gamma_S^5 \qquad lm/W \tag{A-2}$$

[1] Private communication - P. Littlefair, BRE

If $50^0 < \gamma_S < 60^0$ then

$$K_B = 103 + \frac{(\gamma_S - 50)}{70} \qquad lm/W \tag{A-3}$$

If $\gamma_S \geq 60^0$ then

$$K_B = 105 \qquad lm/W \tag{A-4}$$

A.2.2 Diffuse Horizontal Illuminance

The Diffuse Horizontal Irradiance (*Eed*) is converted to Diffuse Horizontal Illuminance (*Evd*) by

$$Evd = K_D Eed \qquad Lux \tag{A-5}$$

where K_D is the diffuse luminous efficacy.

If Solar Altitude $\gamma_S < 5^0$ then

$$K_D = 120 \qquad lm/W \tag{A-6}$$

If $\gamma_S > 5^0$ then

$$K_D = 144 - 29C \qquad lm/W \tag{A-7}$$

where C is the fractional cloud cover

The fractional cloud cover (C) is given by

$$C = 1 - 0.551IN + 1.22IN^2 - 1.68IN^3 \tag{A-8}$$

where IN is the Nebulosity Index

The Nebulosity Index (IN) is given by

$$IN = \frac{\left(1 - \dfrac{Eed}{Eeg}\right)}{(1 - CR_T)} \tag{A-9}$$

where Eed is the diffuse horizontal irradiance, Eeg is the global horizontal irradiance, and CR_T is the theoretical value of Eed / Eeg for a clear sky with a linke turbidity factor $T_L = 3.5$.

CR_T is given by

$$CR_T = \frac{\left(0.0065 + 0.2175\sin^2\gamma_S\right)}{\left(0.0065 + 0.2175\sin\gamma_S - 0.119\sin^2\gamma_S + e^{-3.5\delta_R m}\sin\gamma_s\right)} \quad \textbf{(A-10)}$$

where δ_R is the Raleigh Optical Thickness and m is the Optical Air Mass

The optical air mass (m) is given by

$$m = \frac{\left(1 - \left(\frac{height}{1000}\right)\right)}{\left(\sin\gamma_S + 0.50572\left(\gamma_S + 6.07995\right)^{-1.6364}\right)} \quad \textbf{(A-11)}$$

If $m < 6$ then

$$\delta_R = \frac{1}{\left(5.4729 + 3.0312m - 0.6329m^2 + 0.091m^3 - 0.00013m^4\right)} \quad \textbf{(A-12)}$$

If $6 < m < 20$ then

$$\delta_R = 6.5208 + 1.7417m - 0.1195m^2 + 0.0065m^3 - 0.00013m^4 \quad \textbf{(A-13)}$$

A.3 Sky model

The empirically derived Perez All-Weather Sky Model [Perez 93] is used to estimate the luminance of a patch of sky.

A.3.1 Relative luminance

The relative luminance (lv), the ratio between the luminance (Lv) of a point on the sky hemisphere, and an arbitrary reference point is given by

$$lv = f(\zeta,\gamma) = \left(1 + ae^{(b/\cos\zeta)}\right) \times \left(1 + c.e^{(d\gamma)} + e\cos^2\gamma\right). \quad \textbf{(A-14)}$$

where ζ is the zenith angle of the point and γ is the angle between the point and the position of the sun. The coefficients a,b,c,d and e are adjustable coefficients, functions of isolation conditions.

A.3.2 Isolation conditions

The five coefficients, a, b, c, d and e, are functions of Sky Clearness (ε), Sky Brightness (Δ) and Solar Zenith Angle (*Z*). Sky Clearness and Sky Brightness, derived from measured weather data, determine the pattern of sky luminance distribution.

Sky clearness (ε) is given by

$$\varepsilon = \frac{\left(\dfrac{(Eed + Ees)}{(Eed + 1.041Z^3)}\right)}{(1 + 1.041Z^3)} \qquad \textbf{(A-15)}$$

where *Eed* is Diffuse Horizontal Irradiance, *Ees* is Direct Normal Irradiance and *Z* is the Solar Zenith Angle.

Sky brightness (Δ) is given by

$$\Delta = \frac{mEed}{Ees_0} \qquad \textbf{(A-16)}$$

where *m* is the Optical Air Mass, *Eed* is Diffuse Horizontal Irradiance and Ees_0 is the Normal Extraterrestrial Irradiance.

A.3.3 Absolute luminance

An absolute value for *Lv* can be obtained by normalising the model to a measured value of illuminance.

$$Lv = \frac{lvEvd}{\int_{2\pi sr} [lv(\zeta, \gamma)\cos\zeta] d\omega} \qquad \textbf{(A-17)}$$

where *Evd* is the horizontal diffuse illuminance.

For computational purposes, this continuous function is approximated to

$$Lv = \frac{lvEvd}{\sum_{p=1}^{n} S_P \, lv(\zeta_P, \gamma_P)\cos\zeta_P} \qquad \textbf{(A-18)}$$

where S_P, ζ_P and γ_P are the solid angle, zenith angle and the sun angle respectively, of the patches *(p)* of a sky hemisphere.

The total diffuse horizontal illuminance predicted by the model, the sum of the relative illuminance from all the sky patches, is scaled to match the measured diffuse horizontal illuminance obtained from the weather data and efficacy model.

A.4 Calculating solar position

The position of the sun is defined by a solar altitude angle and a solar azimuth angle [Page 93].

A.4.1 Solar altitude angle

The solar altitude (γ) angle describes how high the sun appears in the sky. It is the angle between the centre of the solar disc and the horizontal plane.

$$\gamma = \sin^{-1}(\sin\phi \sin\delta + \cos\phi \cos\delta \cos\omega) \quad \textit{degrees} \qquad \textbf{(A-19)}$$

where ϕ = Latitude of the site

δ = Solar declination

ω = Solar hour angle

It is sometimes useful to express the Solar Altitude Angle as a Solar Zenith Angle, $\zeta_S = 90 \; - \gamma$

A.4.2 Solar azimuth angle

In the Northern Hemisphere the solar azimuth angle (ψ) is the angle between the vertical plane containing the direction of the sun, and the vertical plane running true north south, measured from south. When the sun is west of south ψ has a positive angle and a negative angle when east of south. The azimuth angle ψ is given by

$$\cos\psi = \frac{(\sin\phi \sin\gamma - \sin\delta)}{(\cos\phi \cos\gamma)} \qquad \textbf{(A-20)}$$

The sign of angle ψ can be found from $\sin\psi$ as follows

$$\sin\psi = \frac{(\cos\delta \sin\omega)}{\cos\gamma} \tag{A-21}$$

If $\sin\psi < 0 \quad \psi = -\cos^{-1}(\cos\psi)$

If $\sin\psi > 0 \quad \psi = \cos^{-1}(\cos\psi)$

In the southern hemisphere, the reference direction is true north. The azimuth angle ψ is given by

$$\cos\psi = \frac{-(\sin\phi \sin\gamma - \sin\delta)}{(\cos\phi \cos\gamma)} \tag{A-22}$$

It is sometimes useful to express the solar azimuth angle as a solar bearing, i.e. and angle relative to true north, positive towards east. When the sun is west of south, $Bearing = 180^0 + \psi$. When the sun is east of south, in the Northern Hemisphere $Bearing = 360^0 - \psi$, in the Southern Hemisphere $Bearing = -\psi$.

The day angle (J') expresses the day number (J), the number of days since January 1st as an angle from 12:00 hours on the 31st December, with a year length of 365.25 days.

J' is given by

$$J' = \frac{J}{365.25} \times 360 \quad degrees \tag{A-23}$$

The local mean time (*LMT*) is the local clock time, and is given by

$$LMT = Hour + \frac{Minute}{60} \quad hours \tag{A-24}$$

The equation of time (*ET*) compensates for the earth's elliptical orbit around the sun and its axial tilt when calculating solar time. *ET* is given by

$$ET = -0.128\sin(J' - 2.8) - 0.165(2J' + 19.7) \quad hours \tag{A-25}$$

The local apparent time (LAT), or local solar time, adjust the local mean time to account for the local time zone, daylight saving time and the slightly irregular motion of the earth around the sun. LAT is given by

$$LAT = LMT + \frac{\lambda + \lambda_R}{15} + ET - c \quad hours \tag{A-26}$$

where λ = Longitude of site

λ_R = Reference Longitude of time zone

c = Correction for daylight saving time

Solar declination (δ) is the angle between the suns rays and the earth's equatorial plane, positive when the sun is north of the equator and negative when south. Solar declination δ is given by

$$\delta = \sin^{-1}\left(0.3978\sin\left(J' - 80.2 + 1.92\sin\left(J^{-2.8}\right)\right)\right) \quad degrees \tag{A-27}$$

The solar hour angle (ω) expresses the time of day in terms of an angle of rotation of the earth, relative to the solar position at noon at a specific place. Each hour corresponds to a rotation of 15^0. ω is given by

$$\omega = 15(LAT - 12) \quad degrees \tag{A-28}$$

Appendix

B Using the DLS

B.1 Introduction

This appendix provides a systematic guide to using the DLS. The way in which geometry files that describe the building to be considered are loaded, how the points at which illuminance is to be calculated are positioned, and how artificial lights are selected and positioned is described. The way the calculation of coefficients is initiated and controlled is then described, followed by how the prediction of illuminance calculations is initiated, and how controlling factors, such as lighting control, building occupancy, etc., are defined. Finally, the way in which artificial lights can be added to and deleted from the database of luminaires is described.

B.2 The building to be modelled

B.2.1 Building Geometry

The building geometry, which is contained in one or more data files, is defined using standard RADIANCE format. The DLS places no theoretical limitation on the complexity of the geometry, and all RADIANCE primitives can be used. The DLS only displays polygons in the wire-frame view, however all geometric primitives will be used in the simulations, as the geometry files are passed to RADIANCE unchanged.

Building geometry is added by selecting 'Add geometry...' on the *Building* menu (Figure B.1). When the DLS has read a geometry file, a wire-frame representation is displayed in the main DLS window (Figure B.2). As the DLS performs only simple checks on the geometry files as they are loaded, the RADIANCE program 'oconv' should be used to validate geometry files before they are used. Geometry files should not contain any light sources.

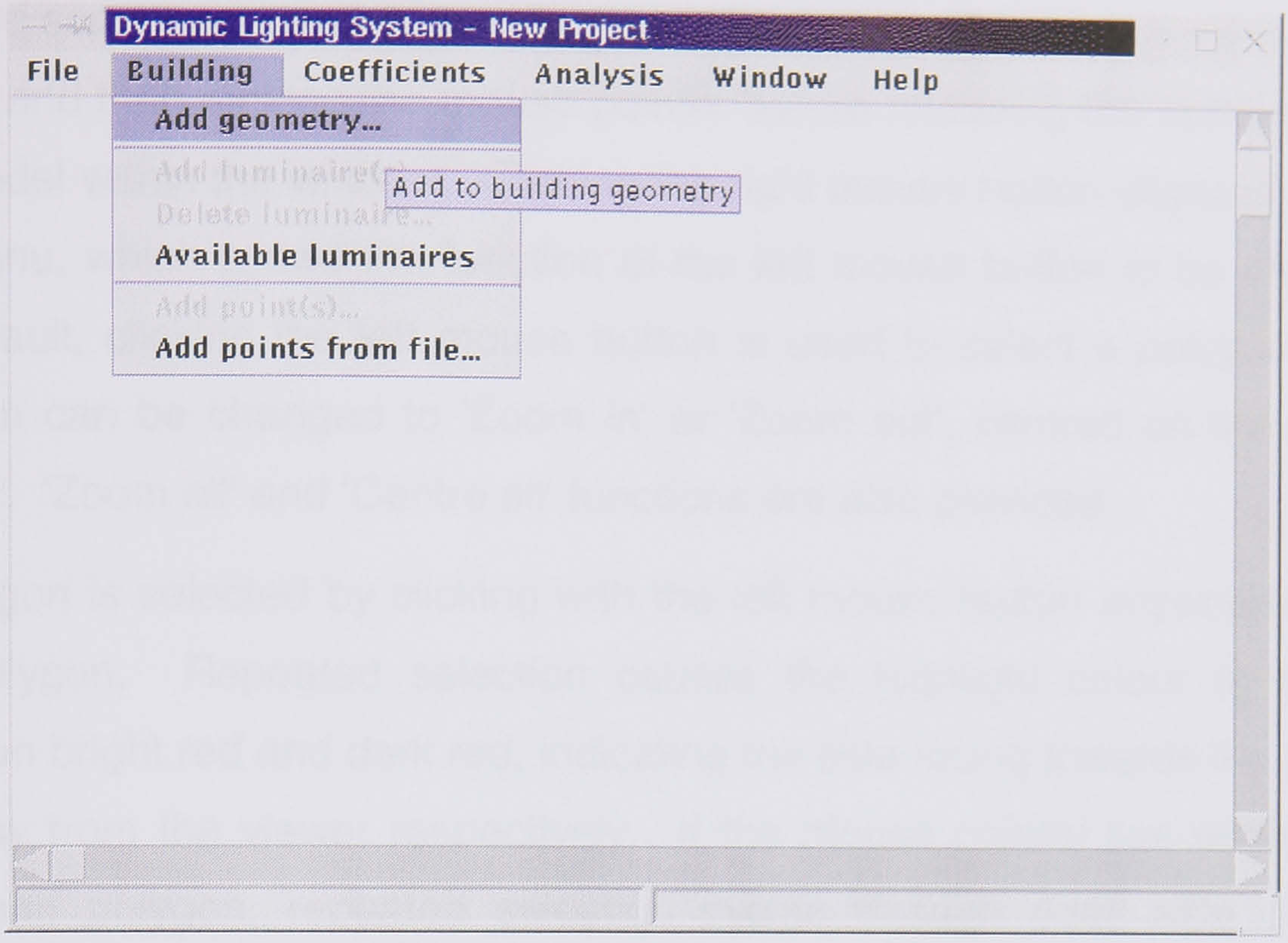


Figure B.1 Loading building geometry from file

B.2.2 Wire-frame Viewer

The DLS displays a 3D 'wire-frame' view of the polygons defining the building geometry (Figure B.2). When geometry is first loaded, it is shown in plan view, i.e. viewed from above.

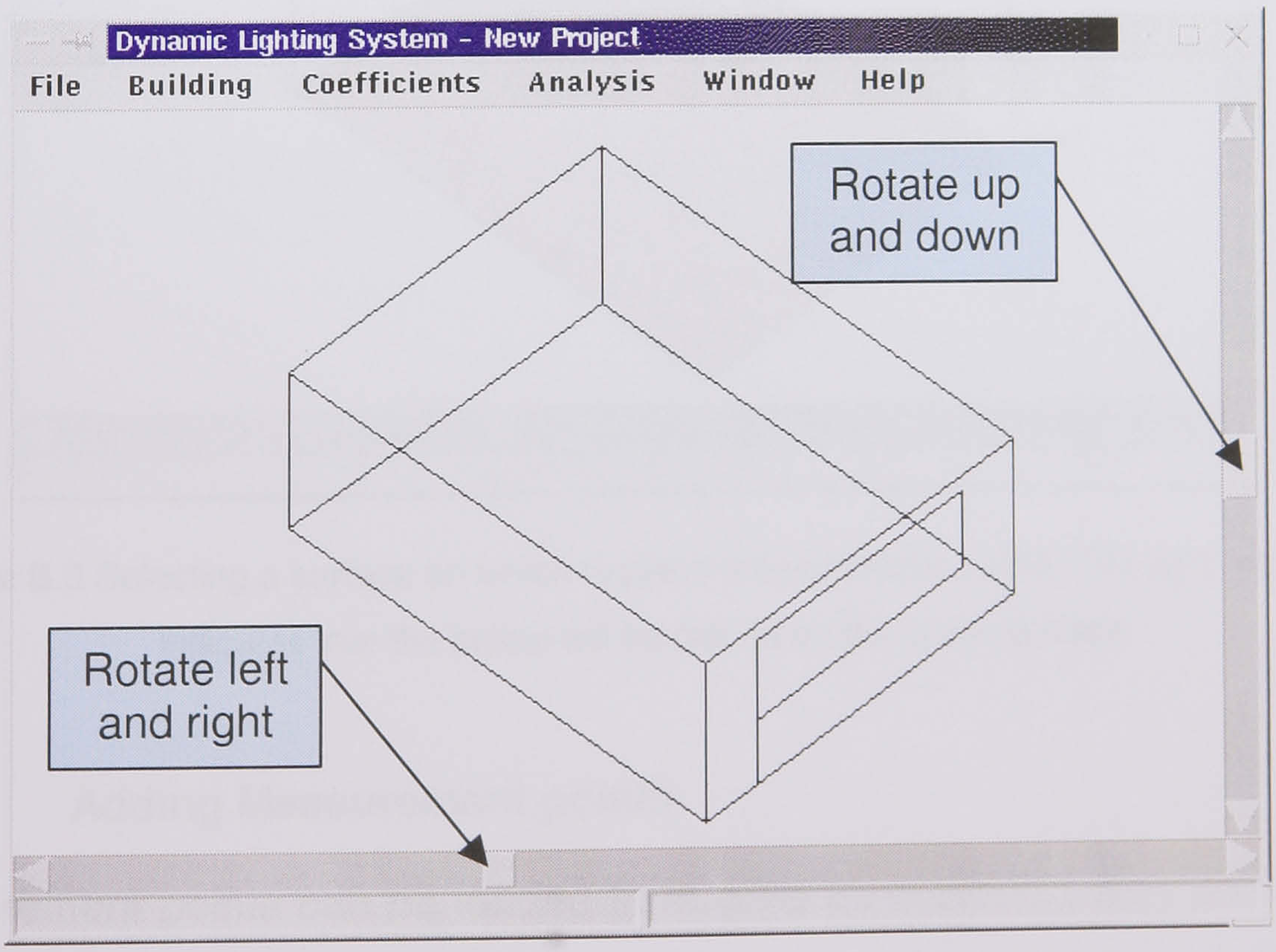


Figure B.2 Wire-frame view of a room with a single window

The two scroll bars can be used to rotate the model. Pressing the left mouse button and then moving the mouse pointer before releasing the button moves the model within the window. Clicking the right mouse button displays a 'pop-up' menu, which allows the function of the left mouse button to be changed. By default, clicking the left mouse button is used to select a polygon. This function can be changed to 'Zoom in' or 'Zoom out', centred on the mouse pointer. 'Zoom all' and 'Centre all' functions are also provided.

A polygon is selected by clicking with the left mouse button anywhere inside the polygon. Repeated selection causes the highlight colour to change between bright red and dark red, indicating the side facing towards the viewer, or away from the viewer respectively. If the mouse pointer lies within more than one polygon, repeated selection cycles through each side of each polygon in turn.

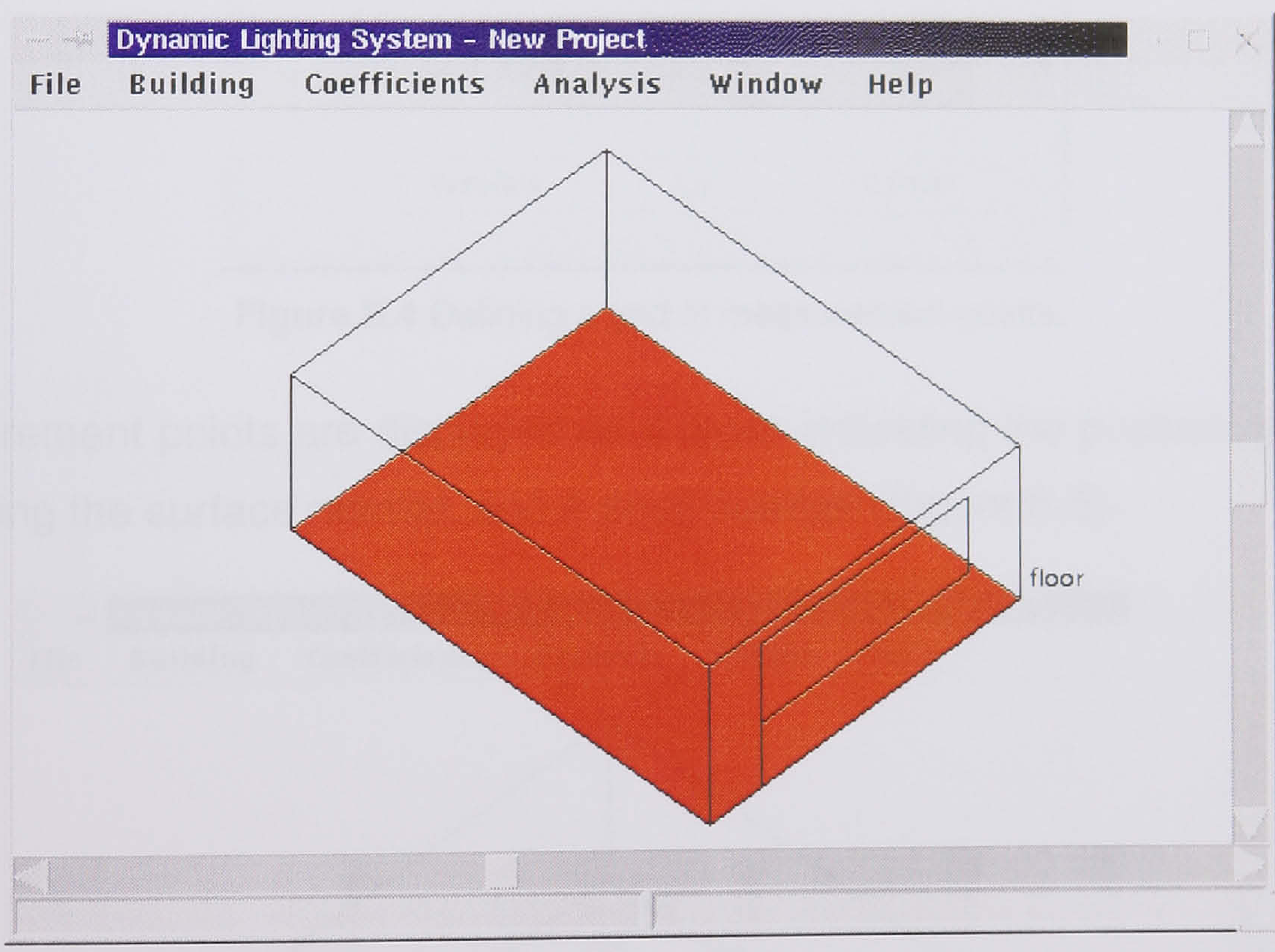


Figure B.3 Selecting a surface on which to place measurement points. The light red colour indicates that the points will be placed on the upper surface

B.2.3 Adding Measurement points

Measurement points can be loaded from a file by choosing 'Add points from file...' on the *Building* menu. Points contained in a file are defined by lines of six numerical values, a position and a direction vector described using x, y and z co-ordinates. Alternatively, a grid of measurement points can be added by selecting a polygon, as described above, then choosing 'Add point(s)...' on the *Building* menu. A dialog box is displayed (Figure B.4) allowing the user to enter the number of rows, number of columns and distance from the surface, e.g. a working plane height. The user can also select whether points should be placed close to, or away from, the edges of the surface. Points can be placed on, or relative to, any polygon, of any shape and with any orientation. Points can be placed on any number of separate polygons.

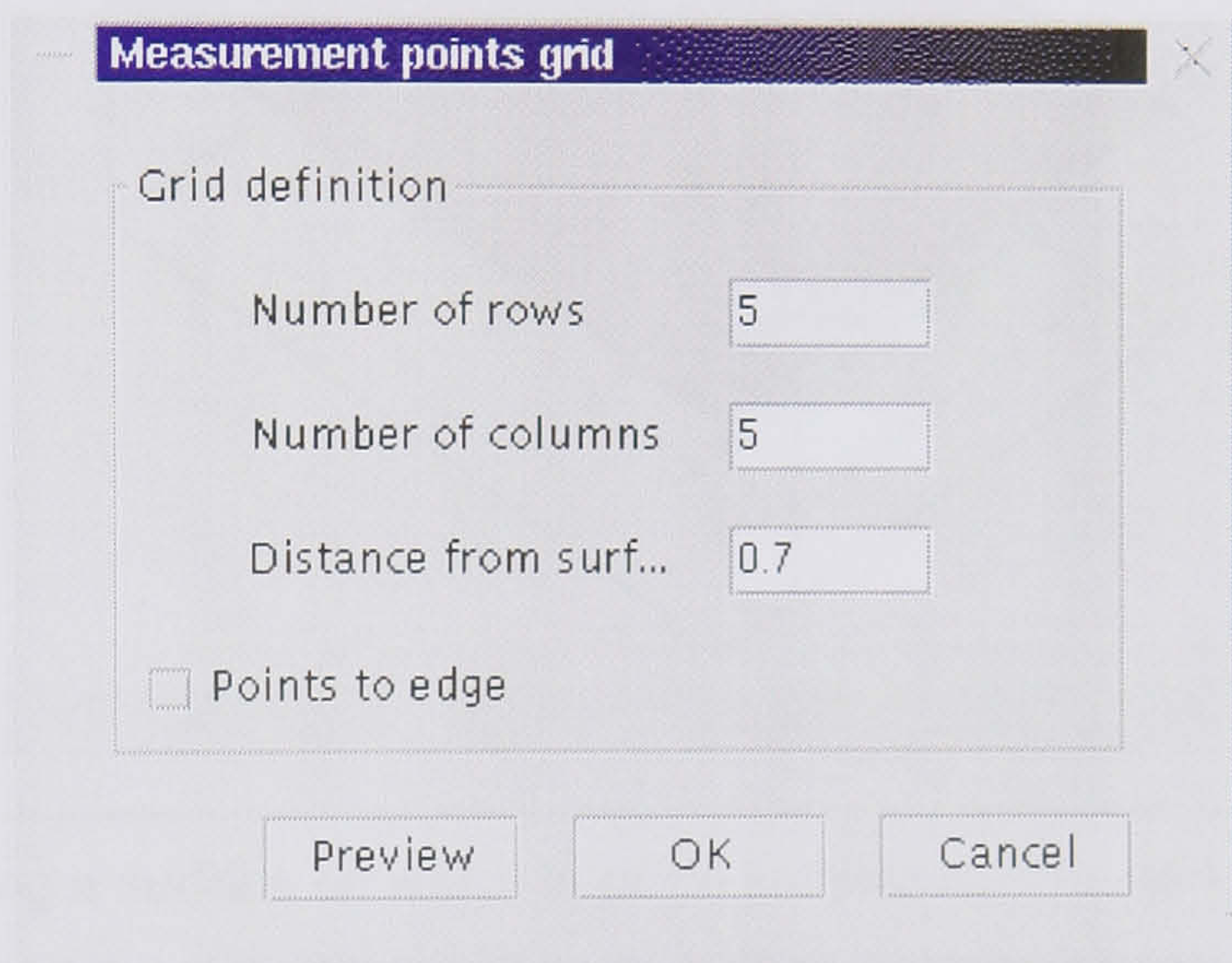


Figure B.4 Defining a grid of measurement points.

Measurement points are displayed as a cross indicating the position, a vector indicating the surface normal, and a point number (Figure B.5).

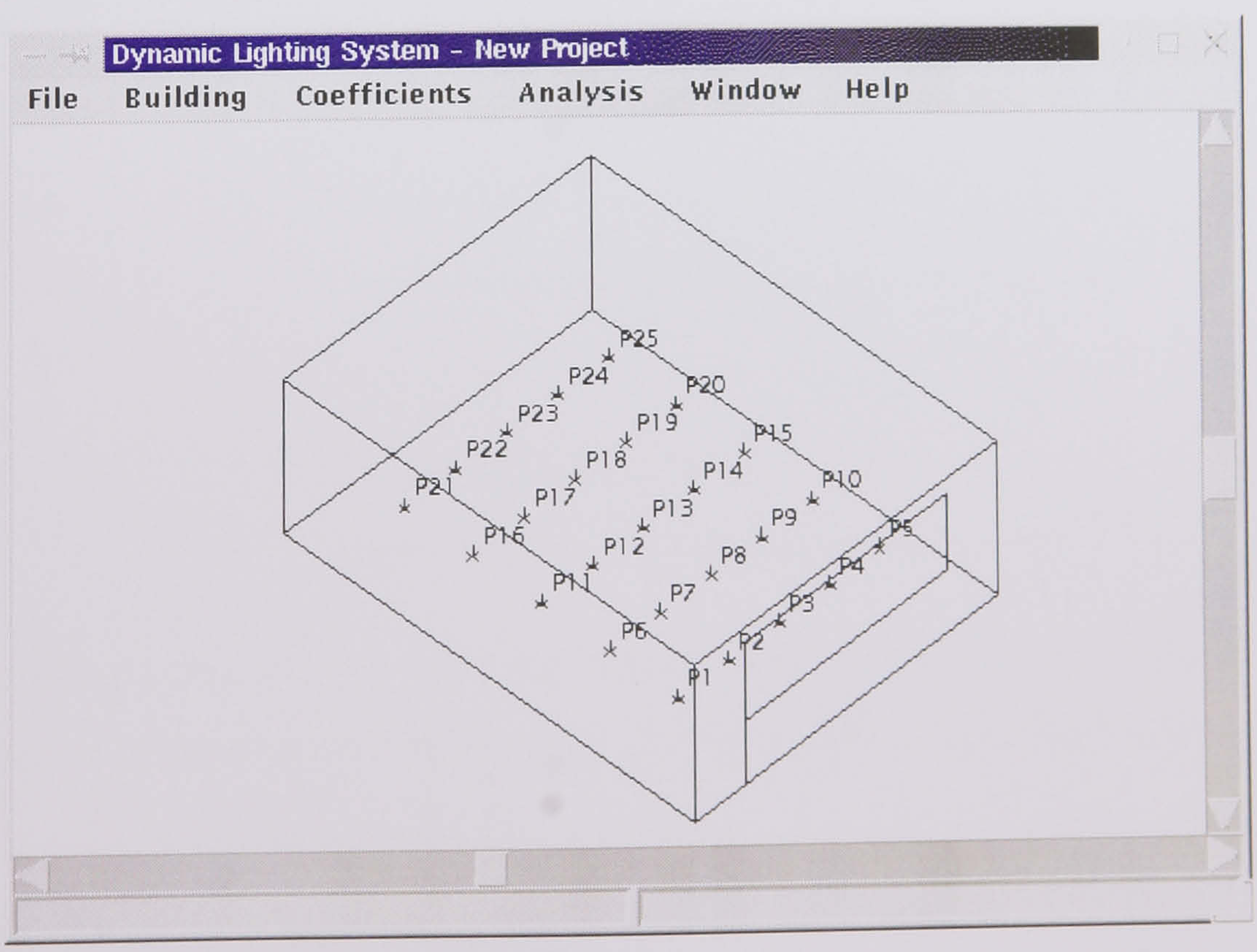


Figure B.5 Measurement points are shown in the wire-frame view

B.2.4 Adding Artificial Lights

A grid of luminaires can be added by selecting a polygon (Figure B.6), as described above, then choosing 'Add luminaire(s)...' on the *Building* menu.

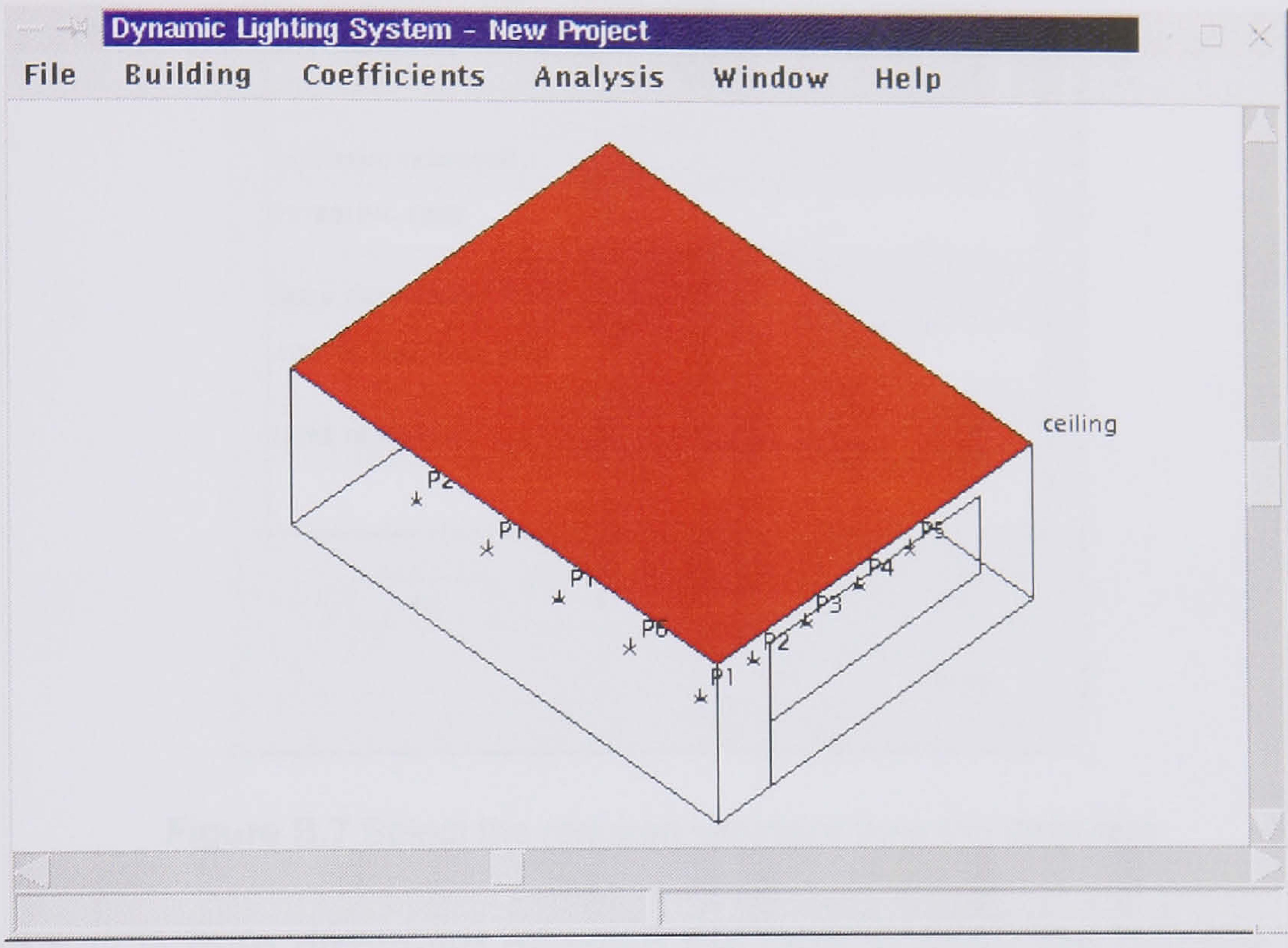


Figure B.6 Selecting a surface on which to place luminaires. The dark red colour indicates that the luminaires will be placed on the lower surface

A dialog box is displayed that allows the user to choose the required luminaire from the database (Figure B.7).

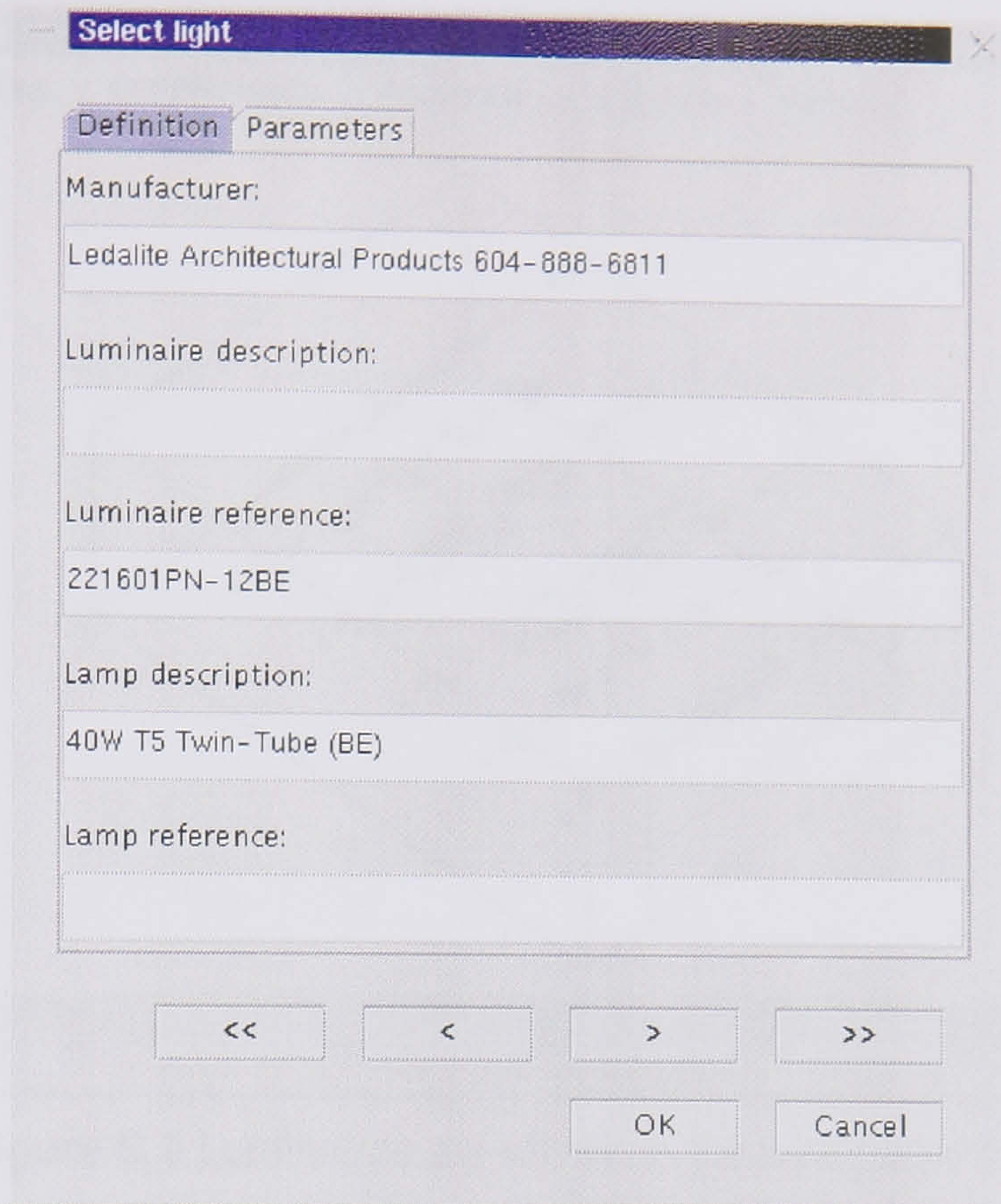


Figure B.7 Select the required luminaire from the database

A dialog box is then displayed allowing the user to enter the number of rows, number of columns and a distance from the surface (Figure B.8). An option to rotate the luminaires by 90^0 is also provided.

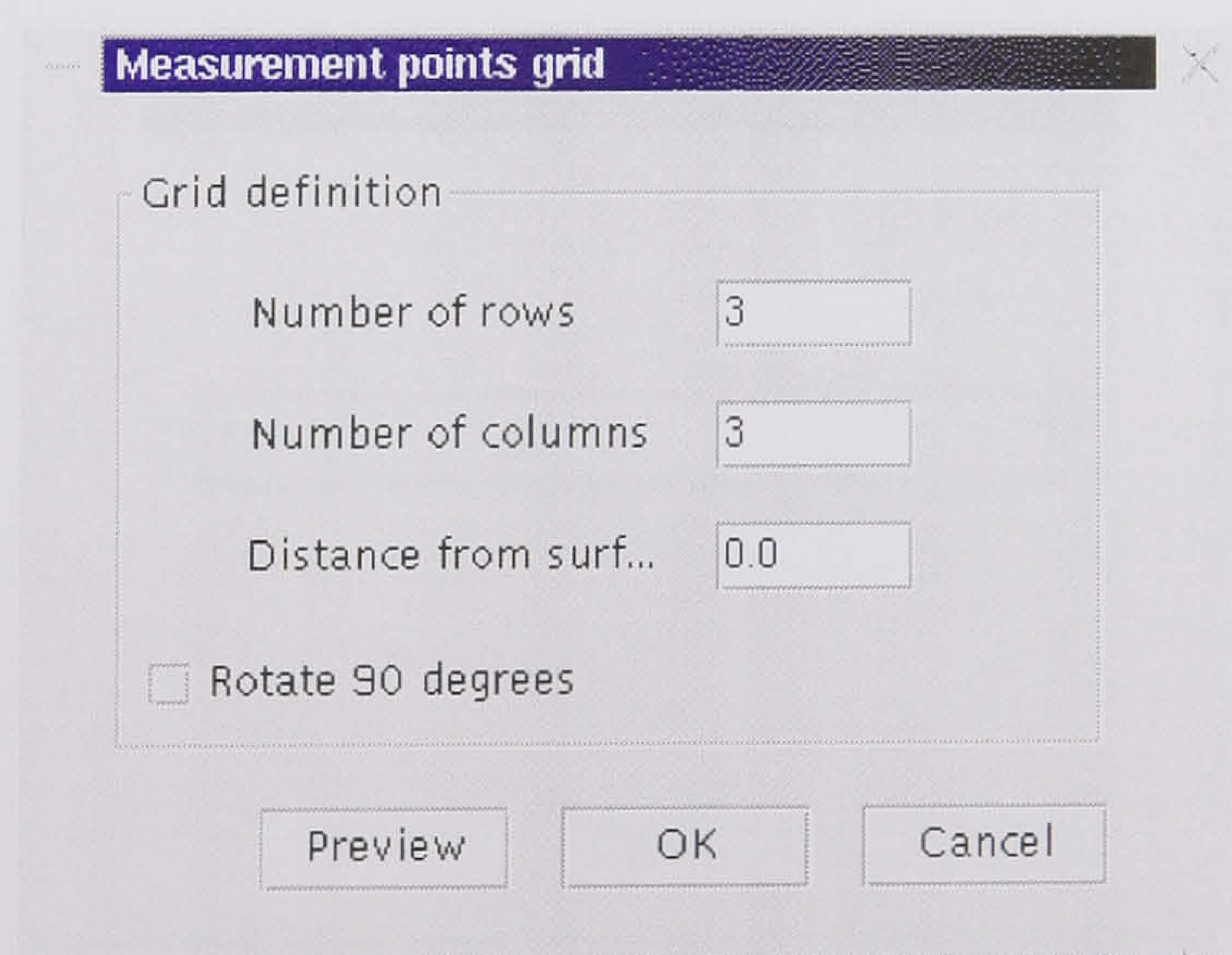


Figure B.8 Define a grid of luminaires

NOTE: Before luminaires can be added, they must first be added to the database of available luminaires, see 'Artificial Lights Database' below.

Luminaires are displayed in the wire-frame view, as a polygon showing the size, orientation and position, and a luminaire number (Figure B.9).

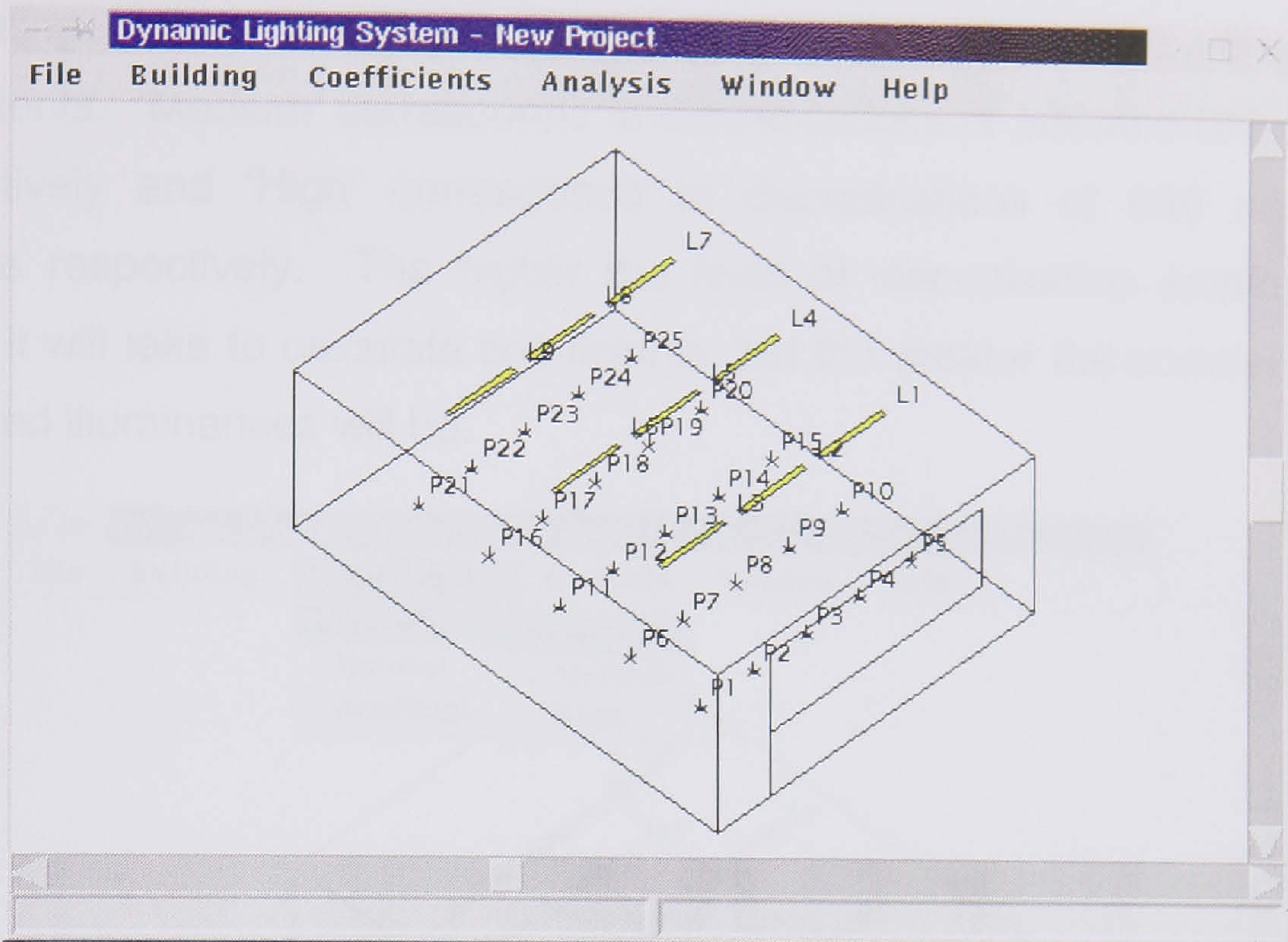


Figure B.9 Luminaires are shown in the wire-frame view

B.2.5 Deleting Artificial Lights

Individual luminaires can be deleted by choosing 'Delete luminaire...' on the *Building* menu then choosing the luminaire to be deleted from the drop-down list (Figure B.10).

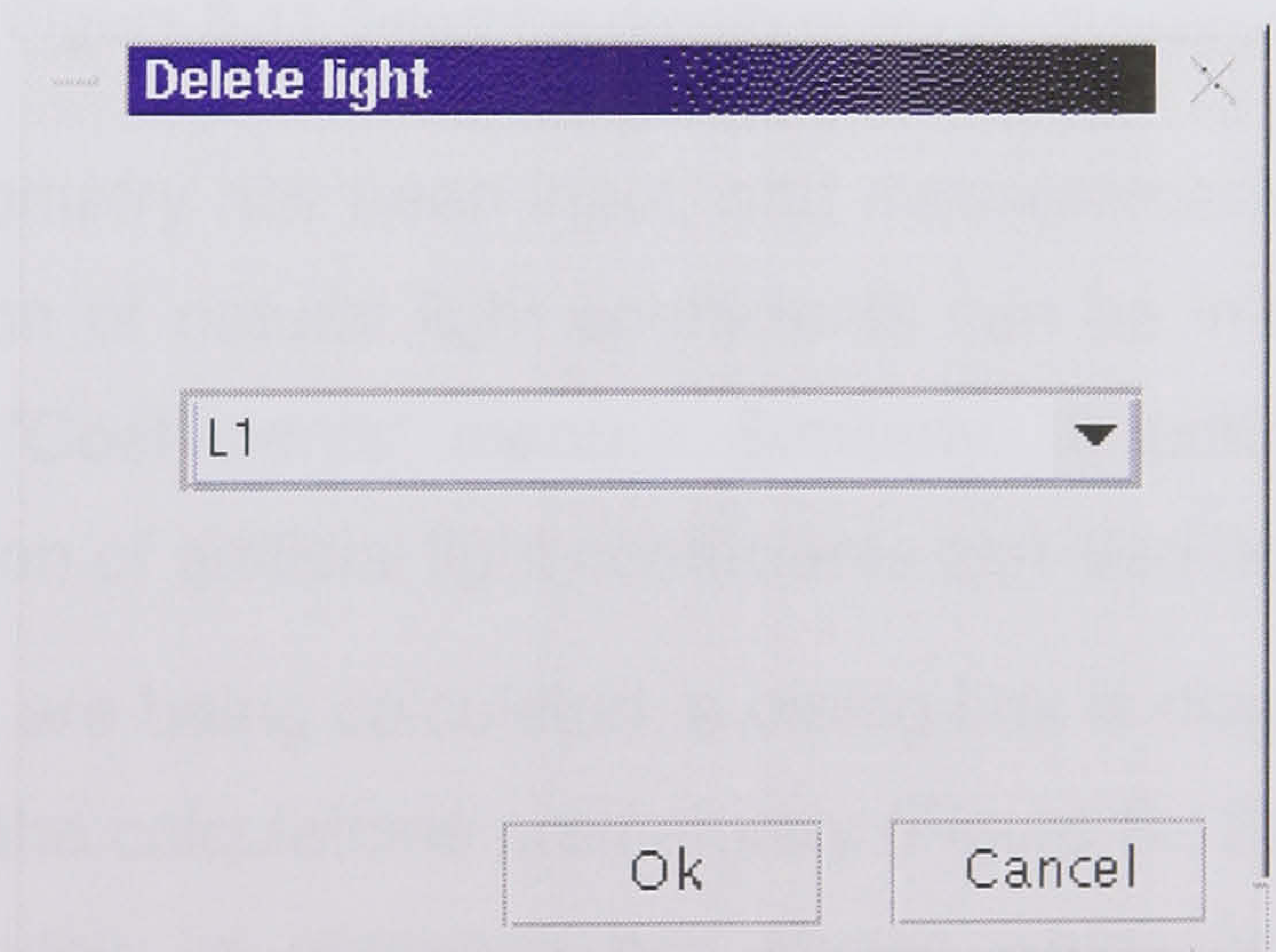


Figure B.10 Select a luminaire to delete from the drop-down list

B.3 Calculating Coefficients

The sky discretisation density for calculating natural light coefficients can be set to 'Low', 'Medium' or 'High', by selecting 'Mode' on the *Coefficients* menu (Figure B.11). 'Low' corresponds to a discretisation of 40 patches when calculating indirect coefficients and 160 patches when calculating direct coefficients. 'Medium' corresponds to discretisations of 160 and 640 patches respectively and 'High' corresponds to discretisations of 640 and 2560 patches respectively. The higher the level of discretisation employed the longer it will take to calculate coefficients, but the greater the accuracy of the predicted illuminances will be.

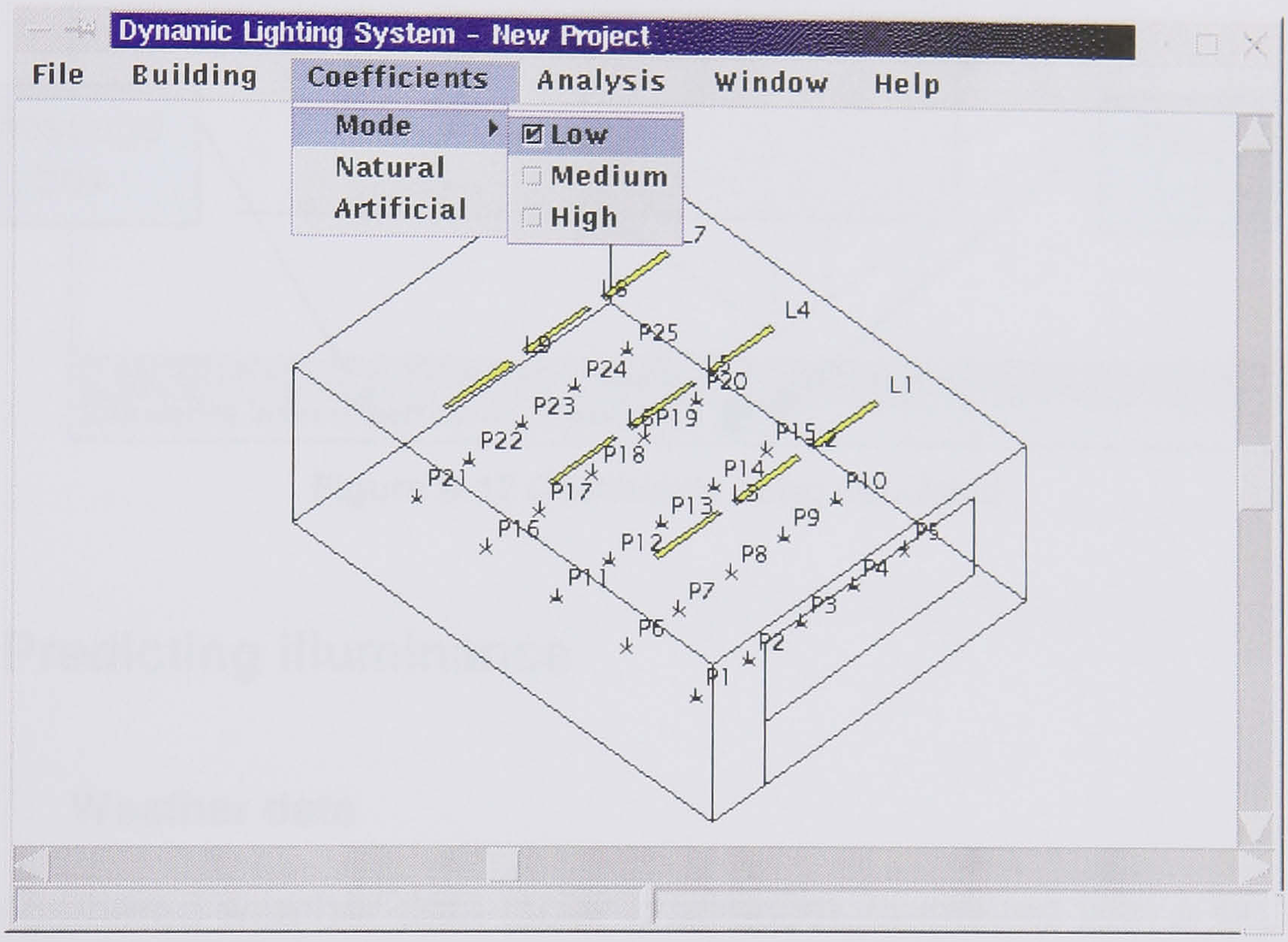


Figure B.11 Select the density of sky discretisation

Once building geometry has been input, and measurement points have been defined, calculation of natural light coefficients can be initiated by choosing 'Natural' on the 'Coefficients' menu. Similarly, if luminaires have been included, calculation of artificial light coefficients can also be initiated.

While coefficients are being calculated, a dialog box is displayed allowing the user to terminate the calculations prematurely (Figure B.12). At the bottom of the geometry window, a message box shows which calculation is being performed, and a 'progress bar' indicates the proportion of all the required calculations completed.

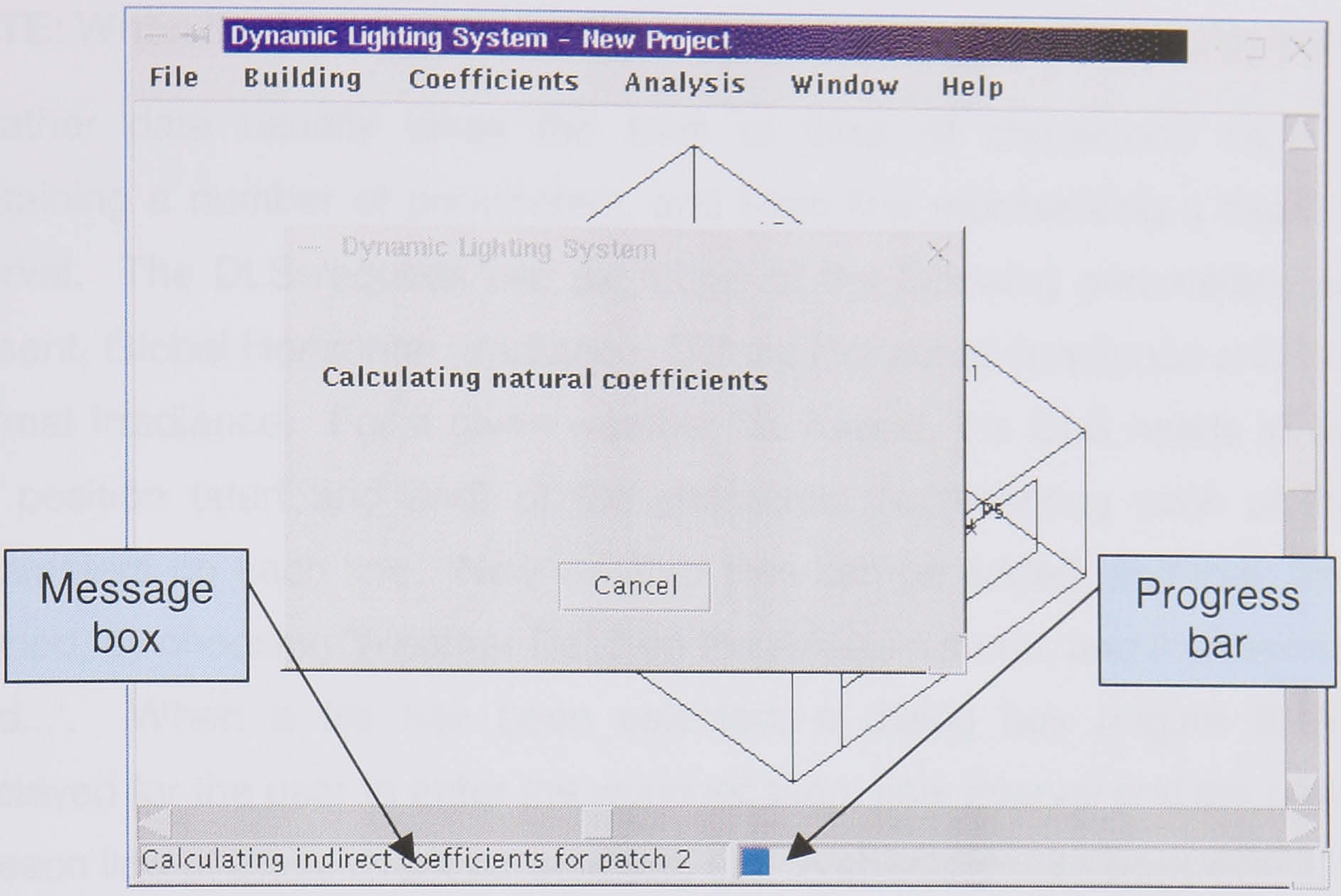


Figure B.12 Coefficients being calculated

B.4 Predicting illuminance

B.4.1 Weather data

Locally gathered weather data (solar irradiance), combined with a sky model, is used to predict natural light from the sky dome and the sun. The weather data file to be used is selected by choosing 'Weather file...' on the *Analysis* menu and then selecting from the list of available files (Figure B.13).

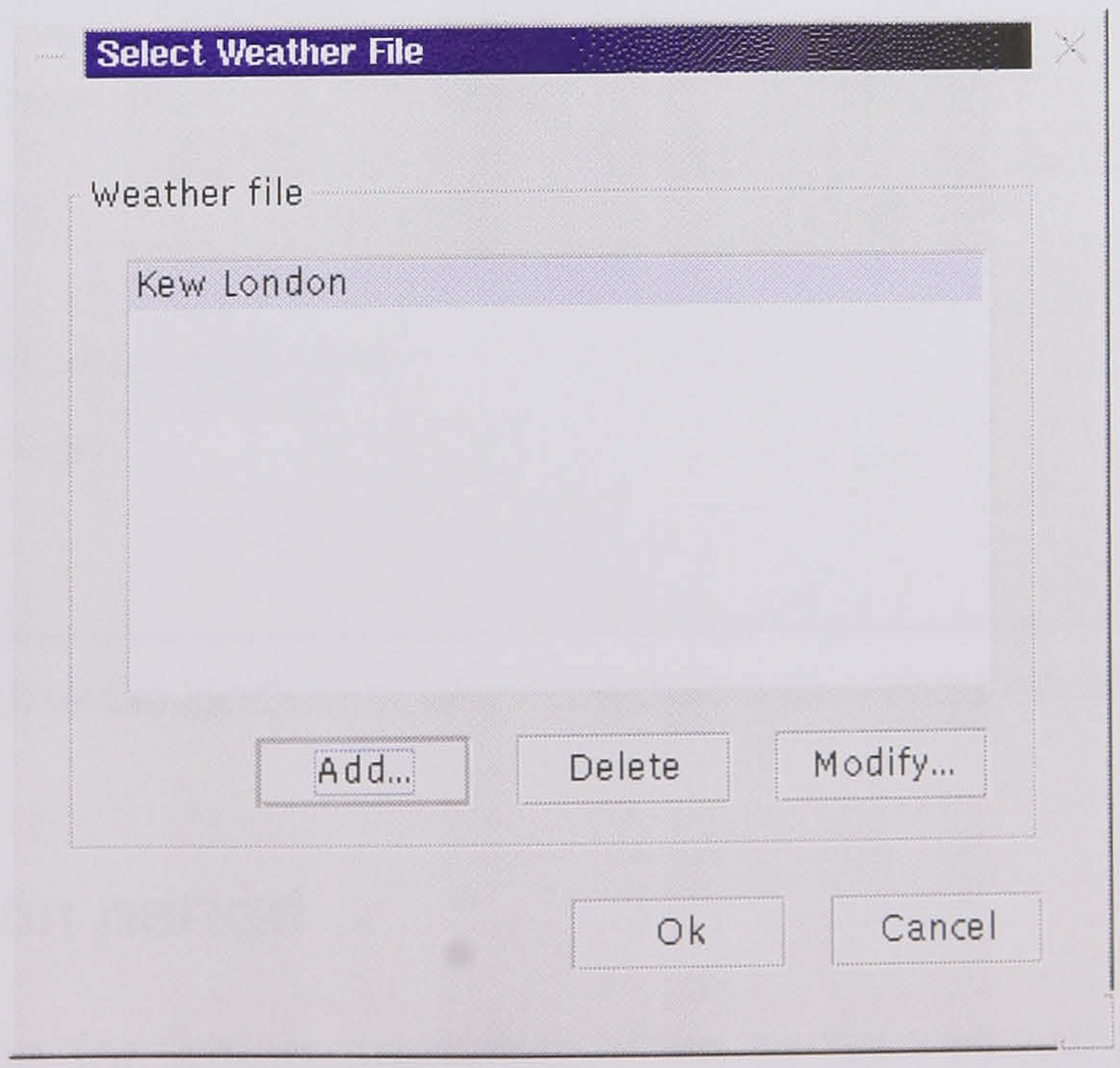


Figure B.13 Select the weather file to be used to model natural light

NOTE: When the DLS is used for the first time, no weather files are defined.

Weather data usually takes the form of lines of characters, each line containing a number of parameters, and each line representing a fixed time interval. The DLS requires two (or more) of the following parameters to be present, Global Horizontal Irradiance, Diffuse Horizontal Irradiance and Direct Normal Irradiance. For a given weather file format, the DLS needs to know the position (start and end) of the characters representing each of these parameters on each line. New weather files can be added, and their format defined, by choosing 'Weather file...' on the *Analysis* menu, and then selecting 'Add...'. When a file has been selected, a dialog box (Figure B.14) is displayed for the user to enter the world location, time interval and the position on each line of the relevant parameters, etc. A character can be specified that indicates the start of comment lines, causing these lines to be ignored.

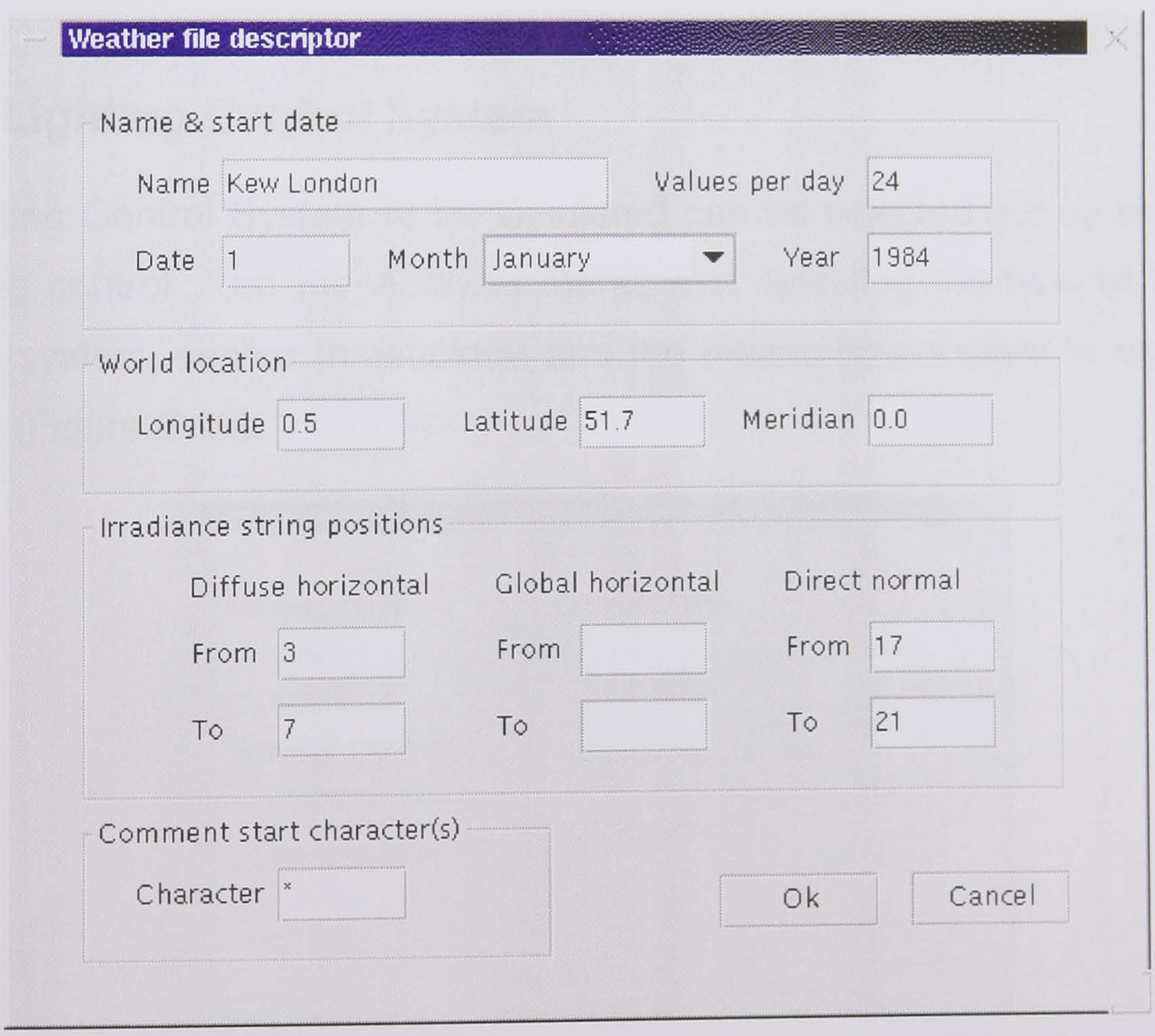


Figure B.14 Define the location at which the data was measured, and the file format

B.5 Simulation period

The period of time for which predictions are to be calculated is specified by choosing 'Simulation period...'on the *Analysis* menu, and then entering the start date, the number of days and the time increment (in minutes). If the time increment specified is less than that of the weather file, the DLS will interpolate the predicted natural illuminance value used by a lighting control system.

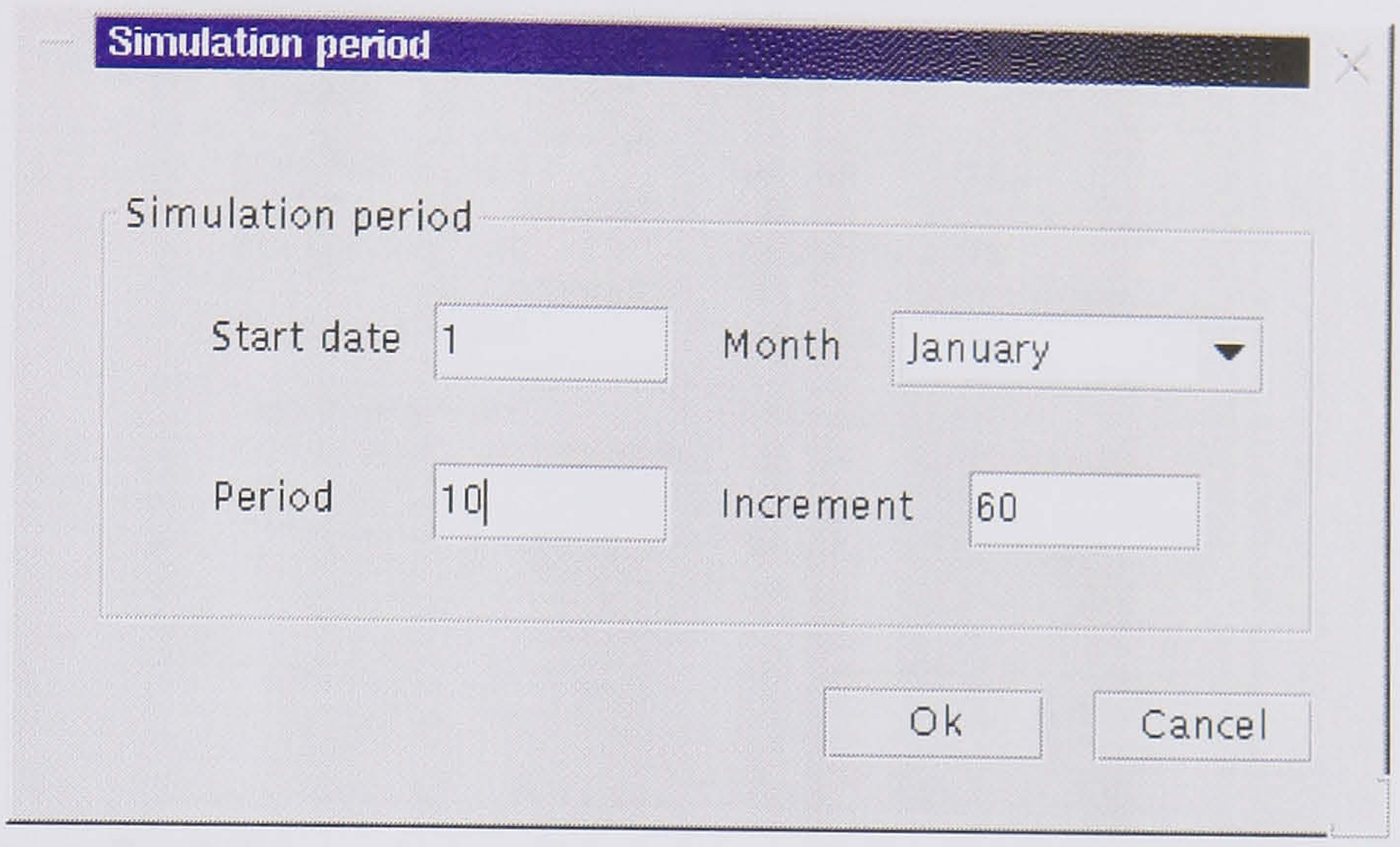


Figure B.15 Time period to predict illuminance values for

B.6 Lighting Control System

A Lighting Control System to be simulated can be selected set by choosing 'Lighting control...' on the *Analysis* menu, and selecting the type of lighting control system, sensor threshold(s) and the measurement point to use as a sensor (Figure B.16).

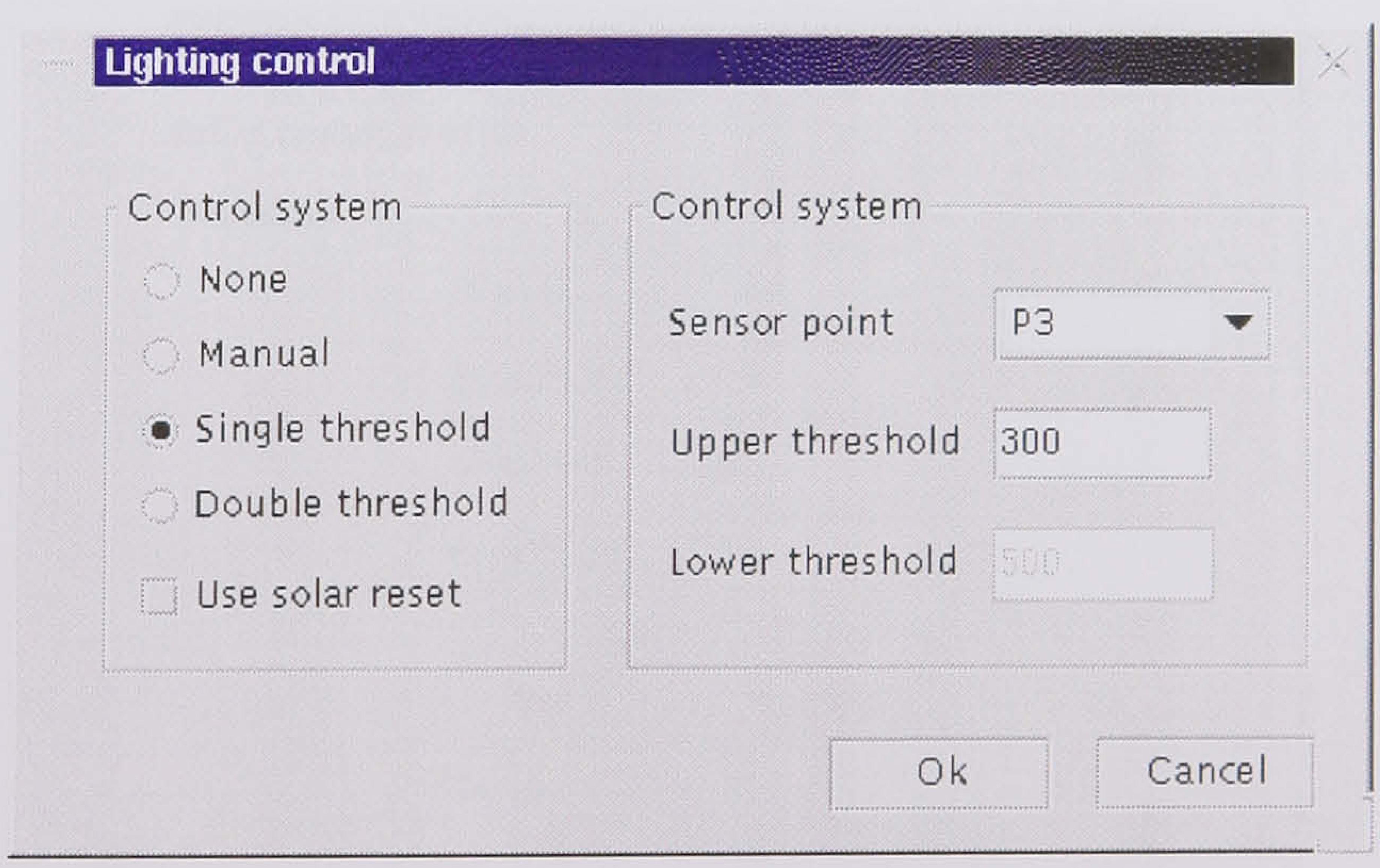


Figure B.16 Select the type of lighting control system to be used

B.7 Occupancy Profile

The pattern of occupancy of the building can be specified by choosing 'Occupancy..' on the *Analysis* menu, and then setting the start and end times for up to four periods, for each day of the week (Figure B.17). The start of the first period and the end of the last period are used to define the length of the working day. Clicking on 'Previous' or 'Next' allows the day of the week to be selected.

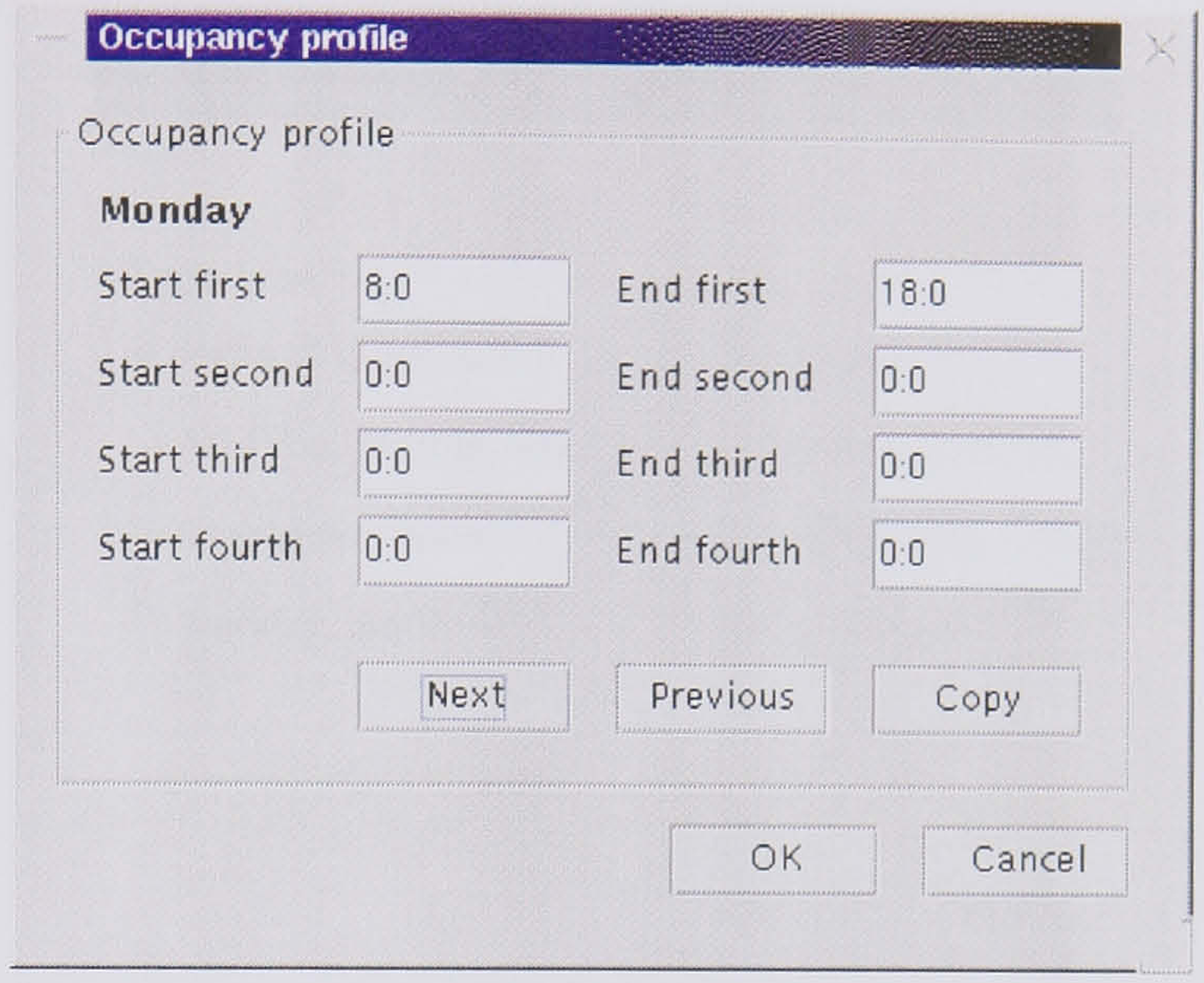


Figure B.17 The periods within each day when the building is occupied

B.8 Solar Reset Profile

The times when lights can be turned off, when natural illuminance is high, can be set by choosing 'Solar reset...' on the *Analysis* menu, and setting up to four times for each day of the week (Figure B.18). Clicking on 'Previous' or 'Next' allows the day of the week to be selected.

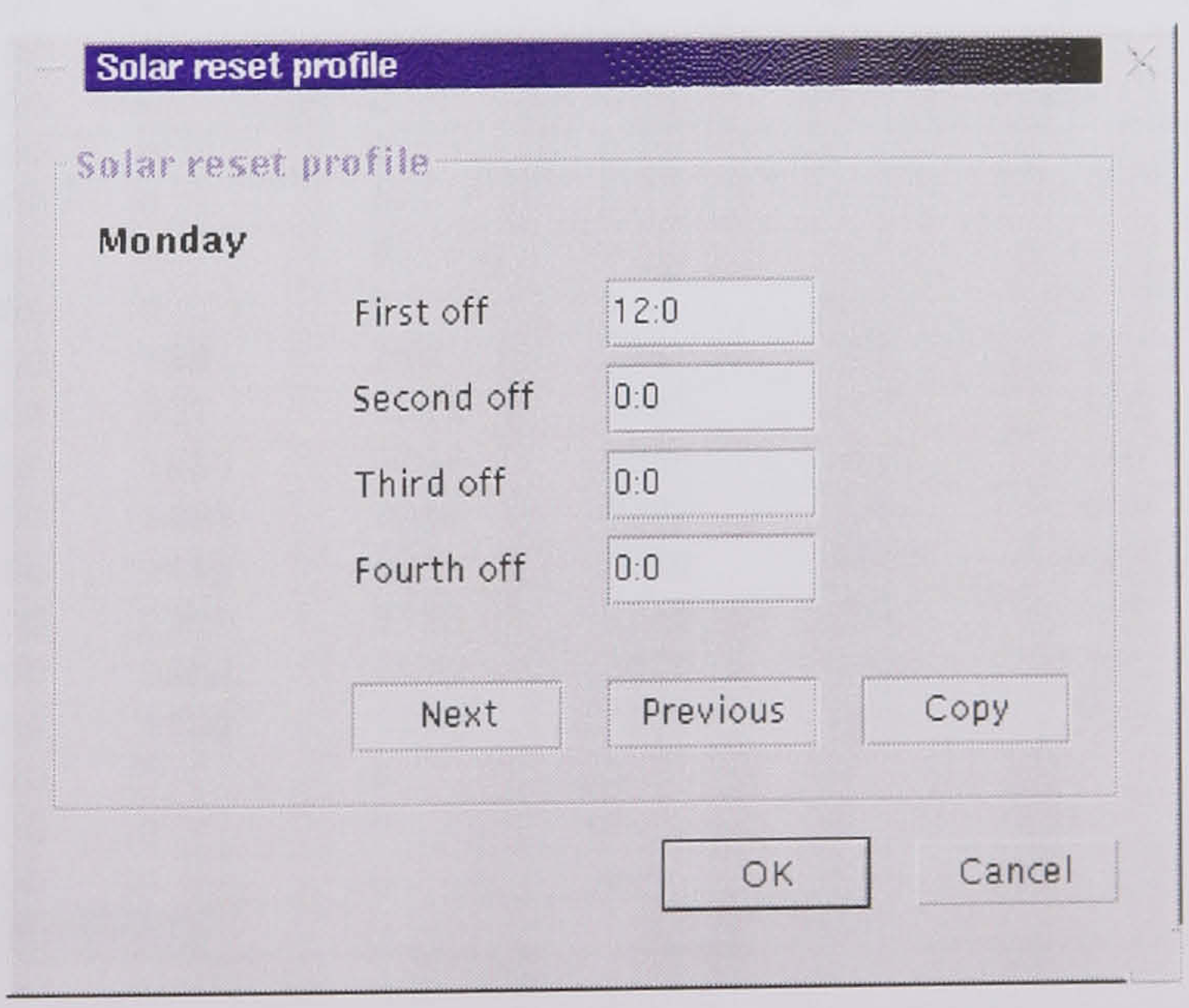


Figure B.18 The times when lights can be automatically turned off

B.9 Selecting required values

An analysis is initiated by choosing 'Analyse...' on the *Analysis* menu, and selecting what type of data and output is required (Figure B.19).

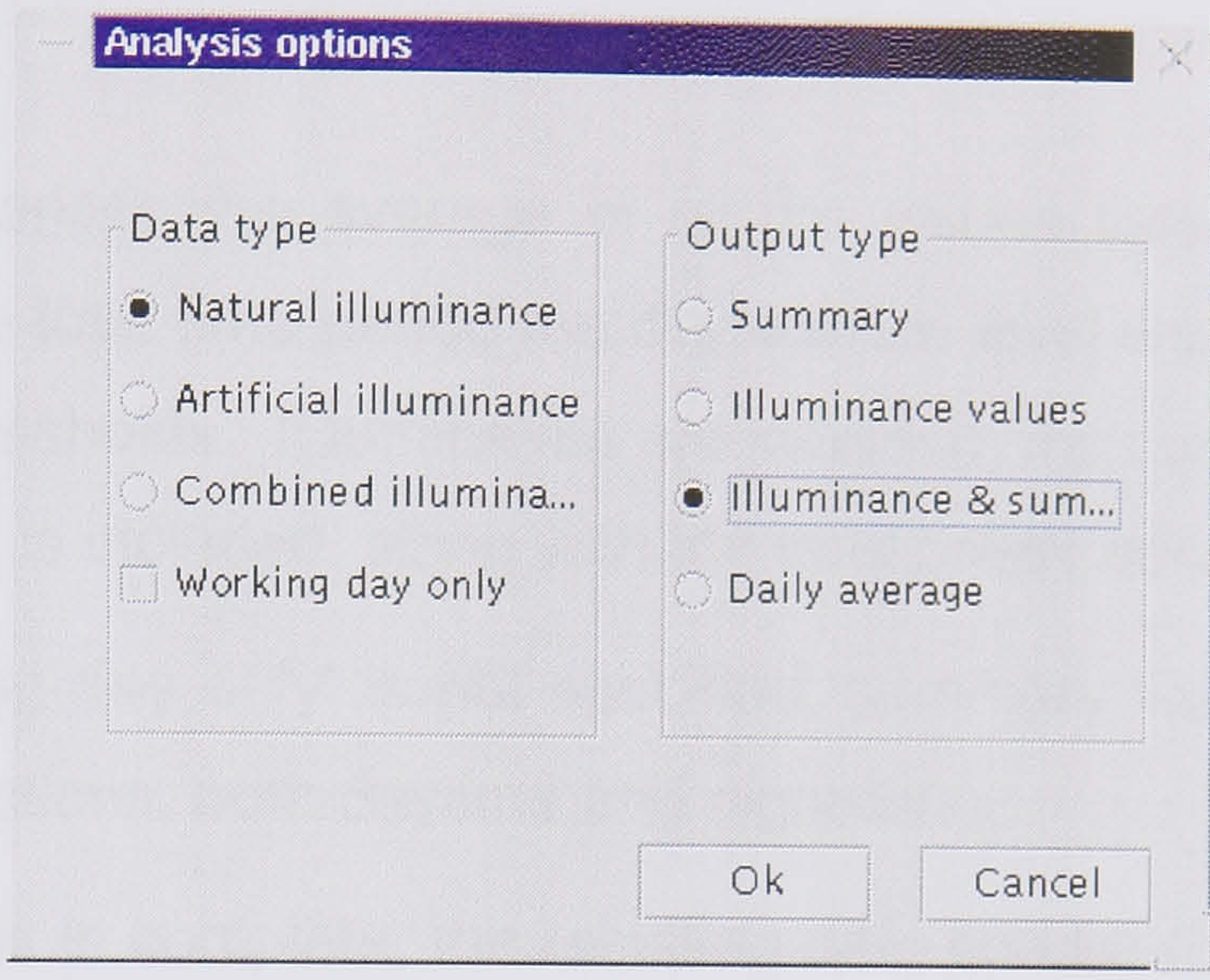
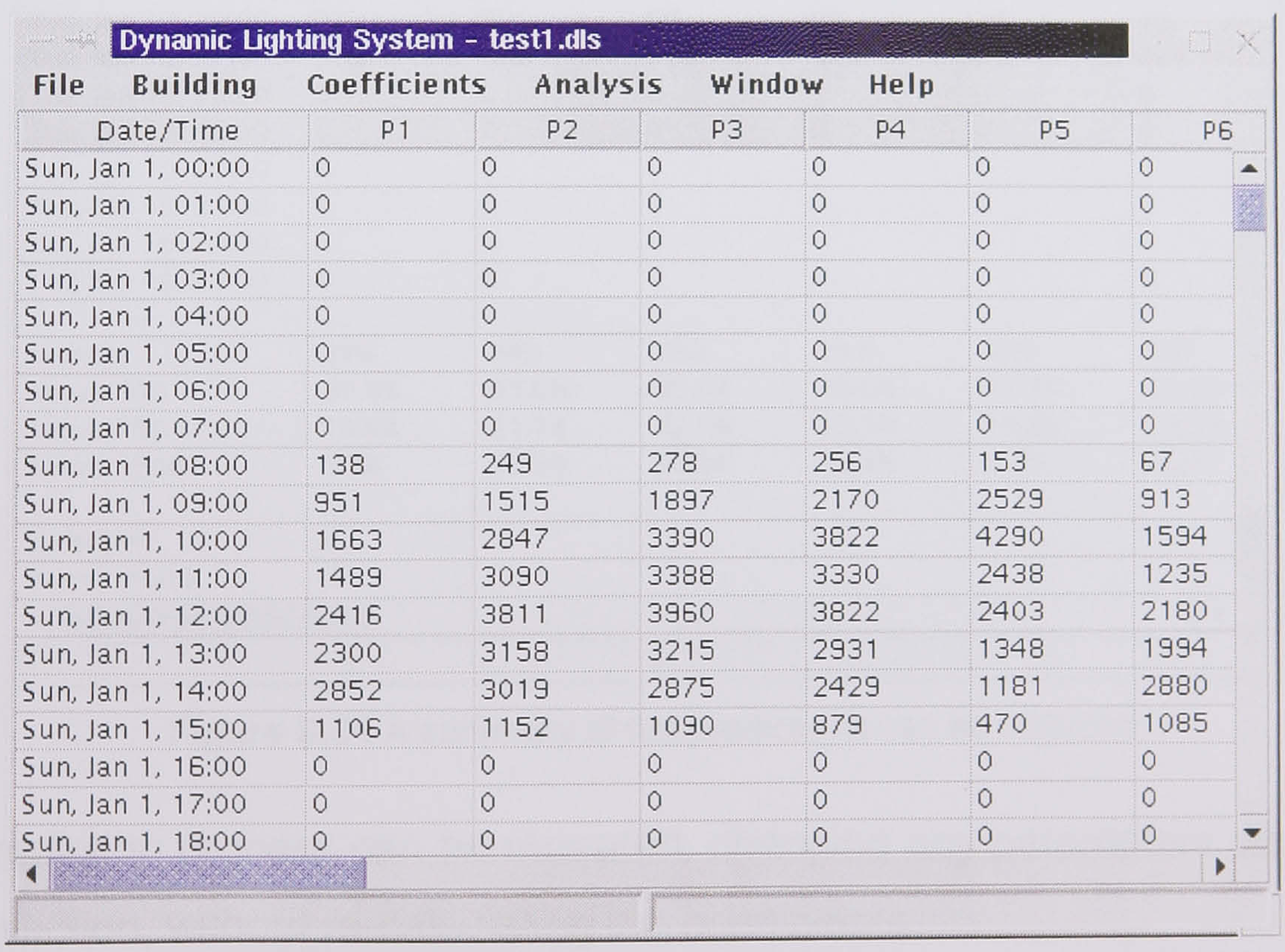


Figure B.19 Select the required output

When the predicted illuminance values have been calculated they are displayed, along with the corresponding date and time, in a spreadsheet style format (Figure B.20).



Date/Time	P1	P2	P3	P4	P5	P6
Sun, Jan 1, 00:00	0	0	0	0	0	0
Sun, Jan 1, 01:00	0	0	0	0	0	0
Sun, Jan 1, 02:00	0	0	0	0	0	0
Sun, Jan 1, 03:00	0	0	0	0	0	0
Sun, Jan 1, 04:00	0	0	0	0	0	0
Sun, Jan 1, 05:00	0	0	0	0	0	0
Sun, Jan 1, 06:00	0	0	0	0	0	0
Sun, Jan 1, 07:00	0	0	0	0	0	0
Sun, Jan 1, 08:00	138	249	278	256	153	67
Sun, Jan 1, 09:00	951	1515	1897	2170	2529	913
Sun, Jan 1, 10:00	1663	2847	3390	3822	4290	1594
Sun, Jan 1, 11:00	1489	3090	3388	3330	2438	1235
Sun, Jan 1, 12:00	2416	3811	3960	3822	2403	2180
Sun, Jan 1, 13:00	2300	3158	3215	2931	1348	1994
Sun, Jan 1, 14:00	2852	3019	2875	2429	1181	2880
Sun, Jan 1, 15:00	1106	1152	1090	879	470	1085
Sun, Jan 1, 16:00	0	0	0	0	0	0
Sun, Jan 1, 17:00	0	0	0	0	0	0
Sun, Jan 1, 18:00	0	0	0	0	0	0

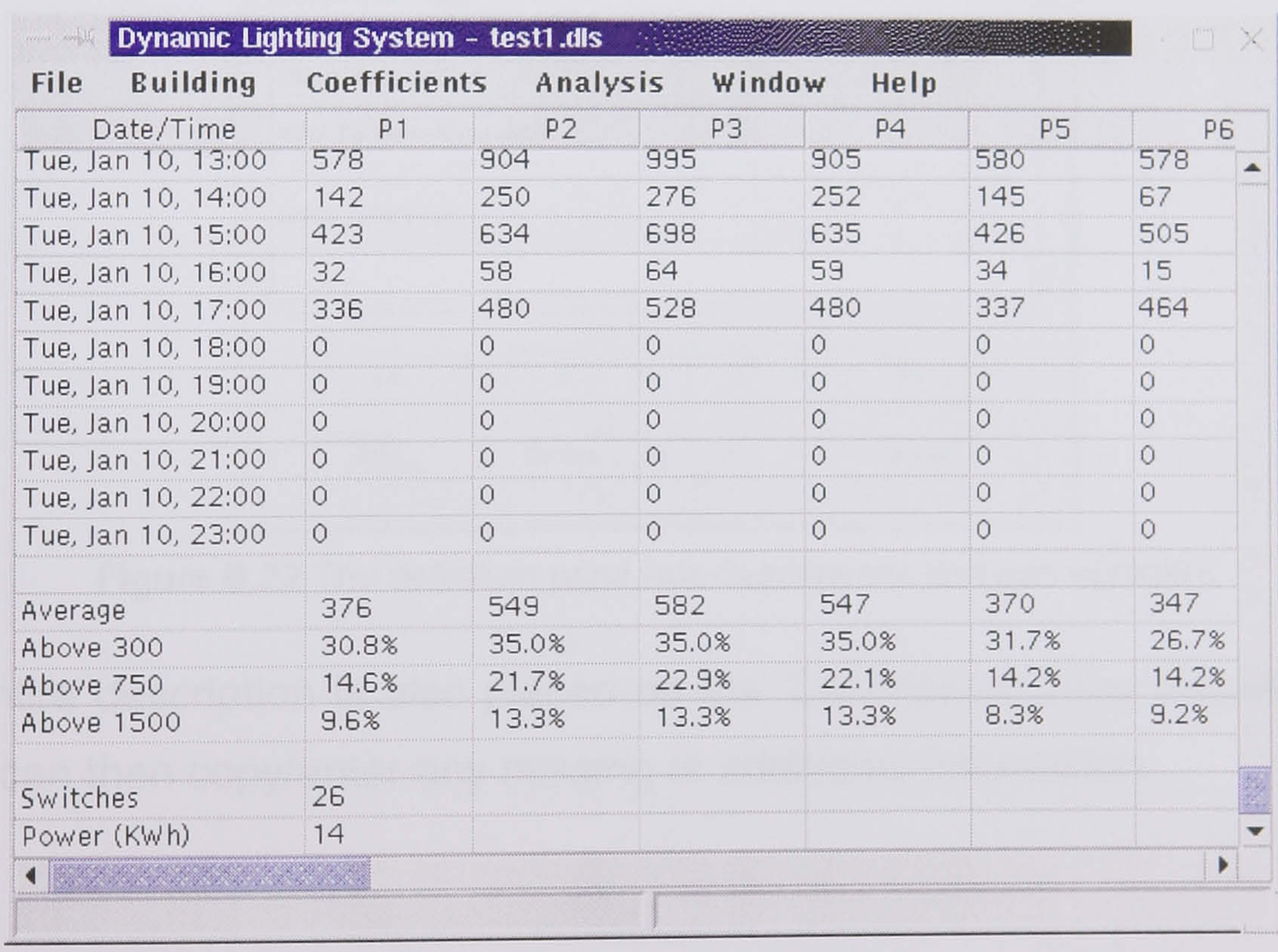
Figure B.20 Predicted illuminance for each measurement point

If luminaires are included, and a lighting control system specified, the user can choose between listing natural illuminance only, artificial illuminance only, or a combination of the two. If 'Working day only' is selected, only values for the times when the building is occupied (determined by the Occupancy profile) are listed. The user can also choose between listing illuminance values only, a summary only or a combination of the two. If a combination is selected, the summary is displayed at the bottom of the list of illuminance values (Figure B.21).

A summary comprises the average of all the values listed above, and the percentage of the total time period the illuminance level was above a number of pre-defined thresholds. If luminaires are included, the number of times they were switched on is included, along with the total power consumption.

NOTE: If 'Working day only' is not specified, summary values will reflect all illuminance predictions, both daytime and night-time.

When the analysis is complete, the resulting data can be dumped to a file by selecting 'Export...' on the *File* menu.



Date/Time	P1	P2	P3	P4	P5	P6
Tue, Jan 10, 13:00	578	904	995	905	580	578
Tue, Jan 10, 14:00	142	250	276	252	145	67
Tue, Jan 10, 15:00	423	634	698	635	426	505
Tue, Jan 10, 16:00	32	58	64	59	34	15
Tue, Jan 10, 17:00	336	480	528	480	337	464
Tue, Jan 10, 18:00	0	0	0	0	0	0
Tue, Jan 10, 19:00	0	0	0	0	0	0
Tue, Jan 10, 20:00	0	0	0	0	0	0
Tue, Jan 10, 21:00	0	0	0	0	0	0
Tue, Jan 10, 22:00	0	0	0	0	0	0
Tue, Jan 10, 23:00	0	0	0	0	0	0
Average	376	549	582	547	370	347
Above 300	30.8%	35.0%	35.0%	35.0%	31.7%	26.7%
Above 750	14.6%	21.7%	22.9%	22.1%	14.2%	14.2%
Above 1500	9.6%	13.3%	13.3%	13.3%	8.3%	9.2%
Switches	26					
Power (KWh)	14					

Figure B.21 A summary of the predictions can be included

This prediction process can be repeated, changing any parameters described in this section, without re-calculating the coefficients.

B.10 Artificial Lights database

The DLS includes a simple database of luminaires. Before luminaires can be used in the DLS, they must first be added to this database. To add luminaires to the database, select 'Available luminaires' on the *Building* menu. Selecting 'Add...' allows an IES format luminaire description file to be selected. When this file is loaded, the information that can be identified in the description part is entered in the appropriate fields Figure B.22).

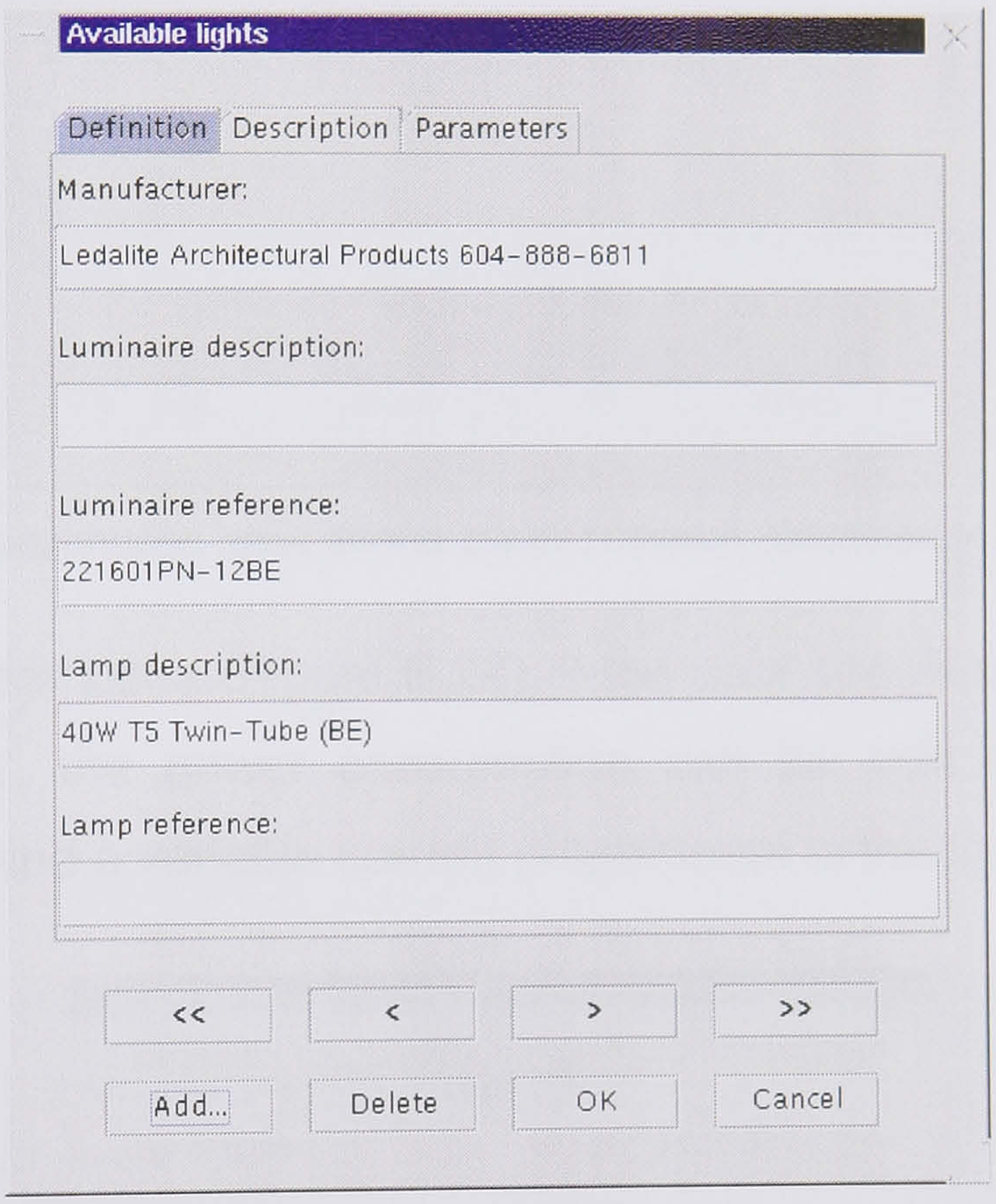


Figure B.22 The definition pane lists descriptions and part numbers

The entire description is also placed on the 'Description' pane (Figure B.23). Users can then copy/enter any missing or additional information.

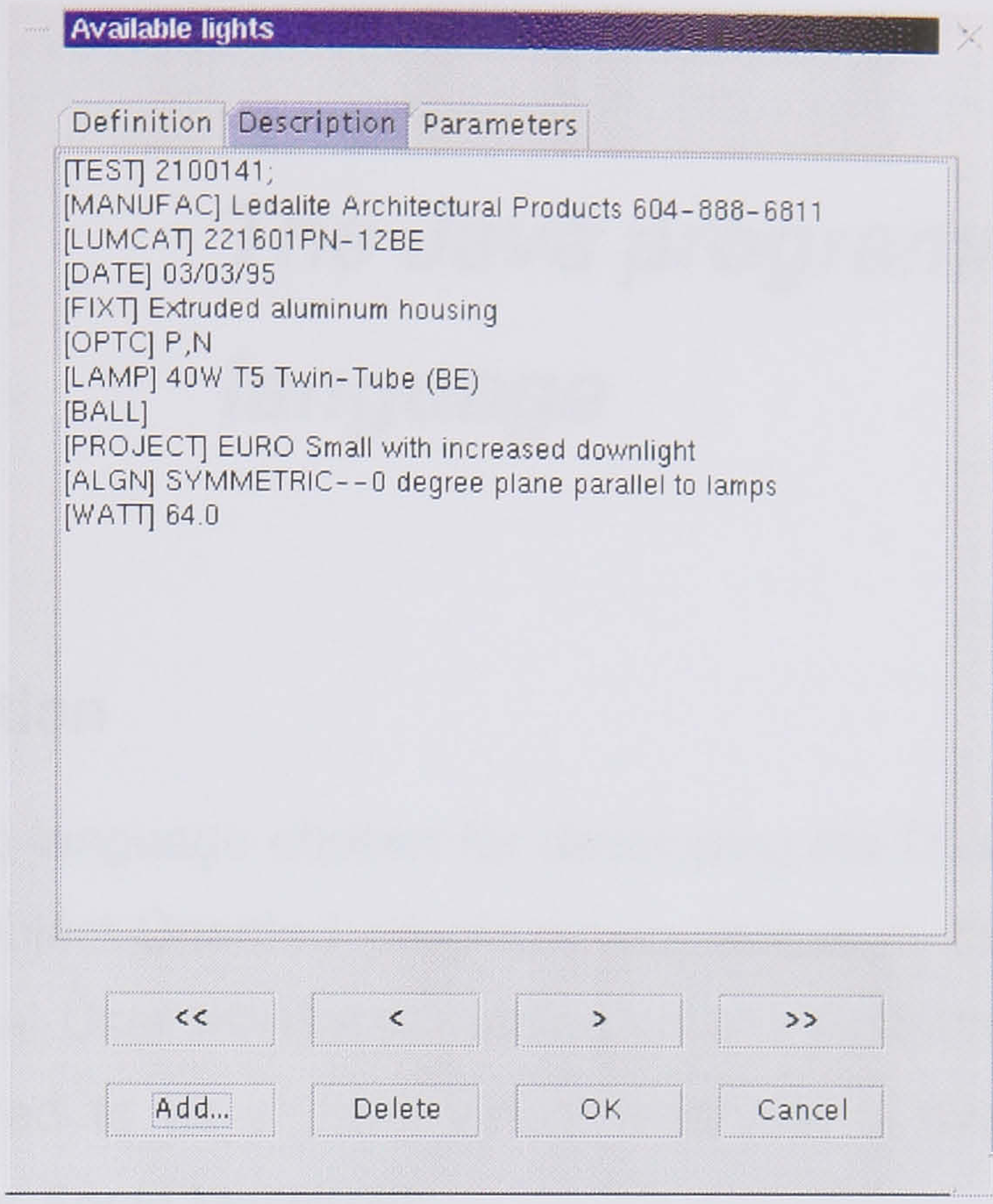


Figure B.23 The description pane shows the information contained in the IES file header

On the 'Parameters' pane (Figure B.24), if the user specifies the luminaire as being 'Dimmable', the power consumption can be split into two parts, a constant current and a variable current proportional to the level of dimming.

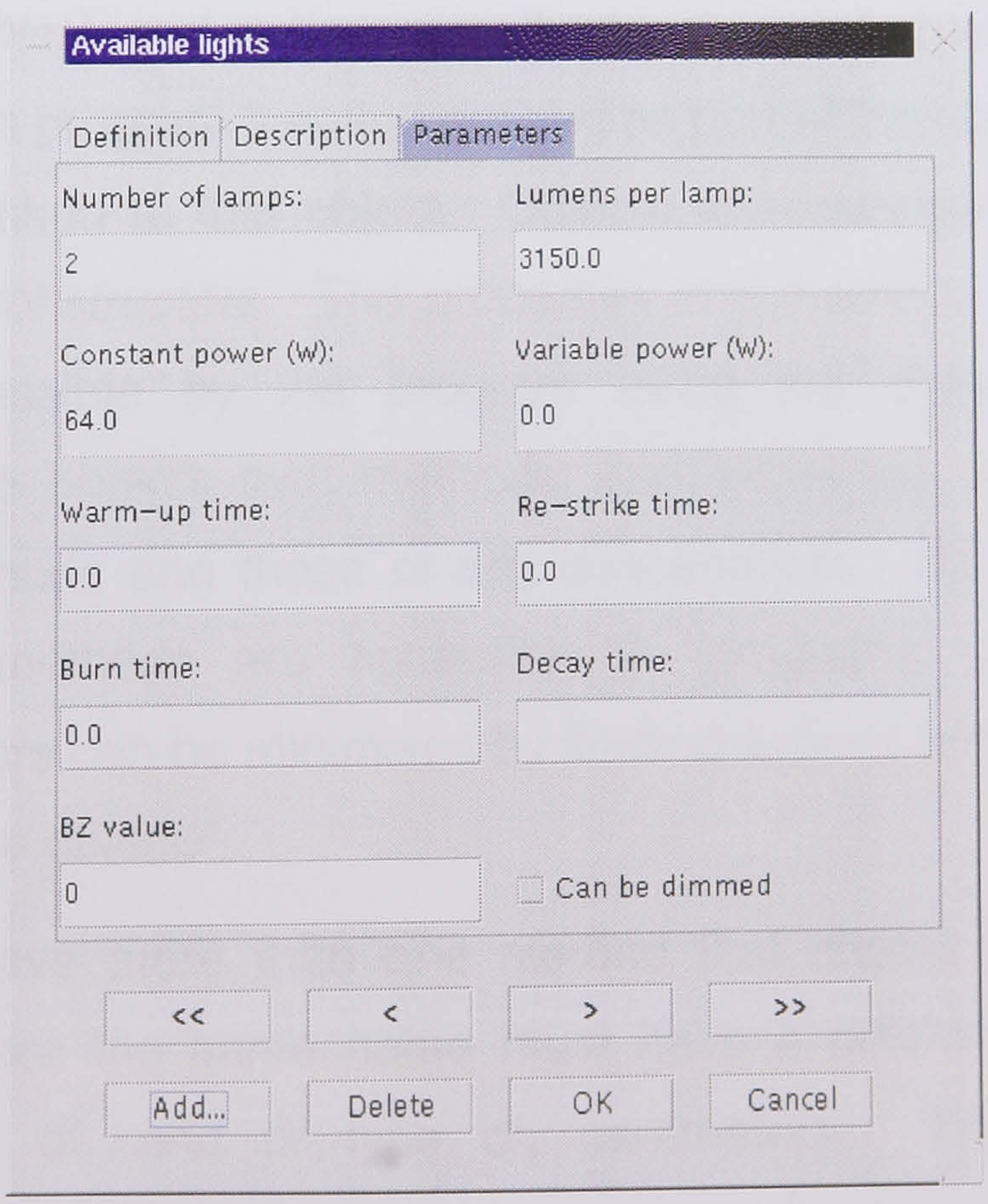


Figure B.24 The parameters pane lists the electrical and luminance characteristics

Appendix

C The Java programming language

C.1 Introduction

The programming language chosen for developing the DLS is Java. Java is an interpreted Object-Oriented programming language that can provide a common Graphical User Interface, running on any platform for which a Java interpreter (referred to as a Java Virtual Machine) is available, e.g. UNIX workstation, PC or Apple Macintosh.

C.2 Object-oriented programming

Object-Oriented Programming (OOP) focuses on the definition and use of *objects*. An object is a logical entity, a user defined data type (*class*) that has properties (*variables*) and actions (*methods*) associated with it. The term method refers to a program function defined as part of the object, that perform actions directly linked to that object. Objects are instantiated using special methods called *constructors*. The properties and methods of an object can be: *public*, accessible by the program using the object; *private*, only accessible by the objects own methods; and *protected*, accessible by the objects own methods and those of any descendants. By controlling which properties and methods are accessible to programs using the object, programming errors can be minimised by limiting actions to those intended by the designer of the object.

An object can have more than one method that shares the same name. Methods that share the same name must have a different interface i.e. a different number of, and or type of, parameters. This OOP feature, *overloading*, allows operations that are conceptually the same to share the same name. Methods can be either *instance* methods or *static* methods. An object's instance methods are methods that perform operations on an individual instance of that object. Static methods perform operations associated with objects of that type, but are not linked to an individual instance. For example, consider an object of type *cuboid*, with properties called *length*, *width* and *height*. The object could have an instance method called *volume*, which has no parameters, and a static method called *volume*, which has three parameters (*length*, *width* and *height*). Individual instances of a cuboid can have different dimensions, and so the instance method would return the volume of that instance of cuboid. The static method would return the volume of a cuboid that has the dimensions supplied, without an instance of a cuboid having to exist.

Another important feature of OOP is *inheritance*, the process by which one object can inherit all the properties and methods of another. This provides support for the concept of classification, where subsequent generations are more specialised forms of the classes from which they inherit. For example, the classification Homo Sapiens is a sub-class of Primate, which in turn is a sub-class of Mammal, etc. In programming terms, a class that inherits from another class can add to, or override (replace) properties or methods defined by the parent class, to produce a more specialised version. This feature of OOP encourages code re-use, reducing development times and reducing errors.

Another feature of OOP is *polymorphism*, which allows different objects to be written that are interchangeable. This is achieved in the Java language by using an *interface specification*, which defines a common set of properties and methods that objects providing that interface must implement. Those objects can then be interchanged provided that any program accessing them uses the interface. For example, the DLS defines an interface that enables new objects to be added that read weather files with different formats, without having to change the main program.

C.3 The Java Virtual Machine

Java is an interpreted language. The term Java Virtual Machine (JVM) is used to refer to the Java interpreter. The Java compiler converts source code into an intermediate form referred to as *bytecode*. This intermediate code can then be 'run' on the virtual machine, which provides a layer of abstraction between the platform independent *bytecode* instructions and the machine specific hardware and operating system. The main advantage of this approach is that, in theory, any Java program can run unaltered on any computer platform for which a JVM is available. In practice, at time of writing this goal has not been fully achieved. The DLS has however been shown to run on both platforms, UNIX workstations and PCs, for which a version of RADIANCE is available.

The main disadvantage is that interpreting *bytecode* is much less efficient than running programs compiled directly to a platform specific form. This is not a major problem under most circumstances. When used to implement a user interface, the slower performance is not noticeable, however when performing computationally intensive operations it can be more significant. Two areas of development are addressing this problem, native mode and Just-In-Time (JIT) compilers. A native mode compiler compiles the Java source code directly to a platform specific form. Whilst the resulting program will only run on the specific platform, a degree of platform independence is maintained because the same source code could be compiled to *bytecode* and run on a JVM, albeit more slowly. A JIT compiler improves the performance of a JVM. While the program is running, portions of the *bytecode* are compiled to a platform specific form as they are encountered by the JVM. These native code fragments are then held in a cache to be available for reuse. If the program repeats the same operation, the cached native code is used, improving the overall speed of operation.